8. RADTRAN CALCULATIONS

8.1 Calculations Performed

Seven sets of RADTRAN calculations and three RADTRAN sensitivity calculations are described in this section. Each calculation develops estimates of the radiological consequences and risks that are associated with the shipment of a single generic Type B cask that contains power reactor spent fuel. Two types of consequences and risks are estimated—those that are associated with the occurrence of accidents during the shipment and those associated with shipments that take place without the occurrence of accidents.

The seven sets of RADTRAN calculations examine four cask designs, two shipment modes, two sets of routes, and three sets of accident source terms. The four generic cask designs examined are steel-lead-steel truck and rail casks, a steel-DU-steel truck cask, and a monolithic steel rail cask. The two shipment modes are truck and rail. The two sets of routes are (a) 200 representative routes selected by Latin Hypercube Sampling (LHS) of route parameter distributions and (b) four illustrative real routes plus the NUREG-0170 shipment route (Illus). The three sets of accident source terms are the NUREG-0170 [8-1] source terms, the Modal Study source terms [8-2], and the new source terms developed by this study.

Table 8.1 lists the seven sets of RADTRAN calculations that were performed and the defining characteristics of each individual calculation. Table 8.1 shows that

- the **first set** of calculations examines the risks associated with shipping PWR and BWR spent fuel by truck (T) in steel-lead-steel (SLS T) and steel-DU-steel (SDUS T) casks;
- the **second set** examines the risks of performing these shipments by rail (R) in steel-lead-steel (SLS R) and monolithic steel (Mono R) casks;
- the **third set** examines the risks of shipping PWR spent fuel by truck in a steel-lead-steel cask over the following five illustrative (Illus) shipment routes: Crystal River Nuclear Plant in Florida to Hanford, Washington (C/H), Maine Yankee Nuclear Plant in Maine to Skull Valley, Utah (M/SV), Maine Yankee Nuclear Plant to the Savannah River Site in South Carolina (M/SR), Kewaunee Nuclear Plant in Wisconsin to the Savannah River Site (K/SR), and the representative truck route examined by NUREG-0170 [8-1];
- the **fourth set** repeats these PWR spent fuel shipment calculations for rail shipments in a monolithic steel cask;
- the **fifth set** examines the influence on spent fuel truck accident risks of the inventory, source term, and exposure pathway models that were used in NUREG-0170;
- the **sixth set** calculates spent fuel truck accident shipment risks using Modal Study and NUREG-0170 Model I (Mod I) and Model II (Mod II) source terms; and
- the **seventh set** repeats the sixth set for spent fuel rail shipments.

The three sensitivity calculations examine the dependence of accident risks on rod failure fractions, the risks associated with heavy haul truck transport of spent fuel, and the risks posed by Loss of Shielding (LOS) accidents during spent fuel transport. These sensitivity calculations are described in Sections 8.10.3, 8.11 and 8.12 respectively.

Table 8.1 Characteristics of Sets of RADTRAN Calculations

Set	Calc.	Routes		Inventory[a]			Severity and Release Fractions														Exp. Paths		Section where calculation discussed
		LHS	Illus	This Study		0170	This Study								NUREG-0170				Modal Study		All	Inhal	
							SLS T		SDUS T		SLS R		Mono R		Mod 1		Mod 2						
				PWR	BWR		PWR	BWR	PWR	BWR	PWR	BWR	PWR	BWR	T	R	T	R	T	R			
1	1	X		X			X														X		Sect. 8.6
	2	X			X			X													X		
	3	X		X					X												X		
	4	X			X					X											X		
2	5	X		X							X										X		Sect. 8.7
	6	X			X							X									X		
	7	X		X									X								X		
	8	X			X									X							X		
3	9		C/H	X			X														X		Sect. 8.10.1
	10		M/SV	X			X														X		
	11		M/SR	X			X														X		
	12		K/SR	X			X														X		
	13		0170	X			X														X		
4	14		C/H	X									X								X		Sect. 8.10.2
	15		M/SV	X									X								X		
	16		M/SR	X									X								X		
	17		K/SR	X									X								X		
	18		0170	X									X								X		
5	19	X		X											X						X		Sect. 8.13
	20	X		X													X				X		
	21	X				X											X				X		
	22	X				X											X					X	
6	23	X				X									X							X	Sect. 8.14
	24	X		X															X		X		
7	25	X				X										X						X	
	26	X				X												X				X	
	27	X		X																X	X		

Table 8.1 also shows that (a) calculations, that do not examine a single specific real route, examine the representative set of 200 truck or rail routes constructed by LHS sampling of route parameter distributions and (b) four of the five calculations, that use the NUREG-0170 inventory, model only radiation exposures occur via inhalation pathways (Inhal).

8.2 The RADTRAN 5 Computational Scheme

The core computation embedded in the RADTRAN 5 code estimates the risks associated with the shipment of a single radioactive material along a single route. Given a radioactive material, package specifications, route data, prevailing weather conditions, an accident source term, and emergency response actions (i.e., population evacuation and decontamination and/or condemnation of contaminated property), RADTRAN 5 calculates the population dose that would result if the specified accident occurs (the accident dose) and if the accident does not occur (the incident-free dose). RADTRAN's computational scheme allows this core calculation to be repeated by looping over additional route segments, weather conditions, and accident source terms. The number of cases that can be examined using this internal loop structure is limited. Therefore, when a very large number of cases needs to be examined, the examination is accomplished using code's Latin Hypercube Sampling computational shell [8-3], which allows large sets of parameter values, selected by sampling from distributions, to be sequentially provided to RADTRAN 5 as separate input files.

8.2.1 Latin Hypercube Sampling

LHS is a structured Monte Carlo sampling method that produces results comparable to those obtained with random Monte Carlo sampling methods using samples that are much smaller than those required by the random sampling methods. Although originally developed to support uncertainty and sensitivity studies, Latin Hypercube Sampling was used in this study to generate representative sets of values for a number of RADTRAN 5 input parameters, for example, route parameters, that can take on a wide range of values in the real world.

8.2.2 Size of the LHS Sample

The size of the LHS sample that provides adequate coverage of the sampled distributions was determined by comparing results calculated (a) with samples of different sizes and (b) with samples of the same size selected using different random seed values. Table 8.2 compares the accident population dose risks (maximum value, minimum value, and the mean value and its standard deviation) obtained for a particular spent fuel shipment calculation using 100, 200, 300, 400, and 500 sets of RADTRAN 5 input selected by LHS sampling. Table 8.2 shows that mean result and its standard deviation are quite stable for samples of size 200 or larger (for example, the mean and standard deviation for the samples of size 200 and 500 are nearly identical), and that increasing sample size beyond 200 principally affects the values of the largest (maximum) and smallest (minimum) observations in the sample. The adequacy of a sample of size 200 was further examined by varying the value of the random seed used to generate the LHS sample. Table 8.3 shows that for samples of size 200, changing the value of the random seed principally affects the values of the maximum and minimum observations in the sample and has little effect on the value of the mean or its standard deviation. Thus, the results presented in these two tables indicate that an LHS sample of size 200 (a sample that contains 200 sets of RADTRAN 5 input values for the parameters sampled) will develop a representative set of values for each sampled parameter (e.g., for the parameters that define the truck and rail routes used in the calculations that examine representative rather than illustrative routes), and consequently reasonable estimates of the mean values for calculated results.

Table 8.2 RADTRAN 5/LHS Accident-Risk Results versus Number of Observations

Observations	100	200	300	400	500
Mean	2.73E-7	2.87E-7	2.90E-7	2.82E-7	2.86E-7
Standard Deviation	2.45E-7	2.83E-7	3.06E-7	2.94E-7	2.85E-7
Maximum	1.13E-6	1.79E-6	1.70E-6	2.34E-6	2.00E-6
Minimum	5.3E-9	1.68E-9	3.42E-9	2.70E-9	1.14E-9

Table 8.3 RADTRAN 5/LHS Accident-Risk Results for 200 Observations versus "Seed"

Random Seed	#1	#2	#3	#4	#5
Mean	2.87E-7	2.96E-7	2.80E-7	2.85E-7	2.78E-7
Standard Deviation	2.83E-7	3.20E-7	2.89E-7	3.13E-7	2.70E-7
Maximum	1.79E-6	1.64E-6	1.71E-6	1.92E-6	1.38E-6
Minimum	1.68E-9	4.17E-9	4.40E-9	8.88E-11	4.47E-9

8.3 Input Parameters and Results Calculated

All of the RADTRAN 5 calculations performed for this study examined spent fuel transported in a Type B cask. All of the routes examined had three aggregate segments, one urban, one suburban, and one rural. Thus, all of the RADTRAN 5 calculations used the following input:

- the cask's spent fuel inventory (three-year cooled, high-burnup PWR and BWR inventories with respective burnups of 60 and 50 gigawatt-days per metric ton of uranium) or the NUREG-0170 inventory that specifies the curie amounts released to the atmosphere during spent fuel transportation accidents of the three radionuclides (Kr-85, I-131, and Cs-137) used to represent all radionuclides contained in the cask inventory;

- 200 representative routes, 1 illustrative route, or the NUREG-0170 route, each having three segments;

- traffic densities and speeds, average vehicle occupancy, accident rates, population densities, and lengths for each of the three aggregate route segments;

- the number of times the spent fuel transport vehicle (the truck or train) stops (e.g., rest stops or stops for inspections), while traversing each segment, the duration of each stop, and the number of people that might be exposed to radiation as a result of the stop;

- the dose rate 1 m from the surface of the spent fuel cask (the package dose rate);

- the weather conditions that prevail while the segment is traversed (the Pasquill-Gifford atmospheric stability class that characterizes the prevailing weather conditions at the time of any hypothetical accident);

- the 19 sets of truck accident release fractions or the 21 sets of train accident release fractions developed for this study, the 8 sets of NUREG-0170 Model I or Model II release fractions, or the 20 sets of Modal Study release fractions;

- the fraction of all possible accidents estimated to cause each set of release fractions (the severity fraction of this type of accident);

- an evacuation time (time after the occurrence of an accident when evacuation of possibly exposed population is completed); and

- values for all of the other RADTRAN 5 input parameters (the parameters that have values that do not depend on the nature of the radioactive material being shipped, the shipment route, the accident source term, prevailing weather, or emergency response actions).

Given this input, each RADTRAN 5 calculation performed for this study calculated

- the incident-free doses incurred by various population groups (e.g., inspectors, persons living along the route, persons traveling in other vehicles on the route) while the spent fuel shipment traveled along each aggregate route segment and the sum of these doses for each population group and for all population groups together (i.e., the total incident-free dose); and

- the accident doses that would result if, during the course of the shipment, the spent fuel truck or train were to be involved in an accident that causes some of the rods in the cask to fail, the cask containment to be compromised, and consequently some radioactive material to be released to the environment.

8.4 Number of Cases Examined

For each route modeled, the number of cases, N_{cases}, examined (core calculations performed) by each RADTRAN 5 calculation is given by $N_{cases} = N_{segments}N_{release\ fraction\ sets}$, where $N_{segments} = 3$ and $N_{release\ fraction\ sets} = 8$ when NUREG-0170 source terms are used; $N_{release\ fraction\ sets} = 20$ when Modal Study source terms are used; and as Table 7.31 shows, $N_{release\ fraction\ sets} = 19$ for truck transport and 21 for rail transport when the new source terms developed by this study are used.

The number of sets of new release fractions examined can be less than the total number of sets of release fractions developed in Section 7, because, as Table 7.31 shows, some of the sets of accident release fractions developed in Section 7 have associated severity fraction values of zero, which means that the accident conditions that lead to the specified set of release fractions are estimated to have zero probability of occurrence (i.e., are estimated to be unattainable during credible accidents). For example, when the steel-DU-steel truck cask is carrying PWR spent fuel, 6 of its 19 sets of release fractions have severity fraction values of zero. Thus, for each route modeled, all of the RADTRAN 5 calculations that used this set of severity fractions and release fractions examined 39 cases where $39 = N_{cases} = N_{segments}N_{release\ fraction\ sets} = 3 \times 13$.

In summary, for each route modeled, the number of cases examined (core calculations performed) by each RADTRAN 5 calculation were as follows: $24 = 3 \times 8$ for calculations that used NUREG-0170 source terms; $60 = 3 \times 20$ for calculations that used Modal Study source terms; and $39 = 3 \times 13$, $45 = 3 \times 15$, and $63 = 3 \times 21$ for calculations that used respectively the steel-DU-steel truck cask source terms, the steel-lead-steel truck cask source terms, and the steel-lead-steel and monolithic steel rail cask source terms developed for this study.

8.5 Complementary Cumulative Distribution Functions

The results calculated for the sets of 24, 60, 39, 45, or 63 cases are displayed as Complementary Cumulative Distribution Functions (CCDFs), which are plots of the probability of occurrence of an accident population dose of a given size or larger (i.e., the probability associated with each consequence value is the sum of the probabilities of that and all larger consequence values). In addition, the area under any of these CCDFs is the expected (mean) population dose risk in person-rem for the set of accidents represented by that curve.

Because 200 different sets of input were examined during each RADTRAN 5 calculation, each of these calculations generated 200-accident dose CCDFs. Figure 8.1 displays the 200 CCDFs that were calculated for the steel-lead-steel cask when that cask was transporting one PWR spent fuel assembly. Because of the density of the CCDF curves plotted in this figure, this plot depicts poorly the information that is embedded in the set of 200 CCDFs that are plotted on the figure.

To better depict the spread of possible consequences and their probabilities of occurrence, four compound CCDFs are constructed. These four compound CCDFs are the expected (mean) result, and the 5^{th}, 50^{th} (median), and 95^{th} percentile results, where for any specific single consequence value the corresponding 5^{th} and 95^{th} percentile probabilities are the probabilities of the CCDFs that lie 10 up from the bottom and 10 down from the top of the set of 200 CCDFs, the corresponding median percentile probability is the average of the probability values for CCDF 100 and CCDF 101, and the expected (mean) result is the average of all of the CCDF probability values that correspond to the specified consequence value.

8.6 Results for the Generic Steel-Lead-Steel and Steel-DU-Steel Truck Casks

The four compound CCDFs that correspond to Figure 8.1 are plotted in Figure 8.2. Specifically, Figure 8.2 presents the expected (mean) CCDF and the CCDFs that represent the 5^{th}, 50^{th} (median), and 95^{th} percentile values of the set of 200 CCDFs that were calculated using the PWR source terms developed for the generic steel-lead-steel truck cask and the representative LHS input sample of size 200. Each element in this LHS sample specified values for all route related

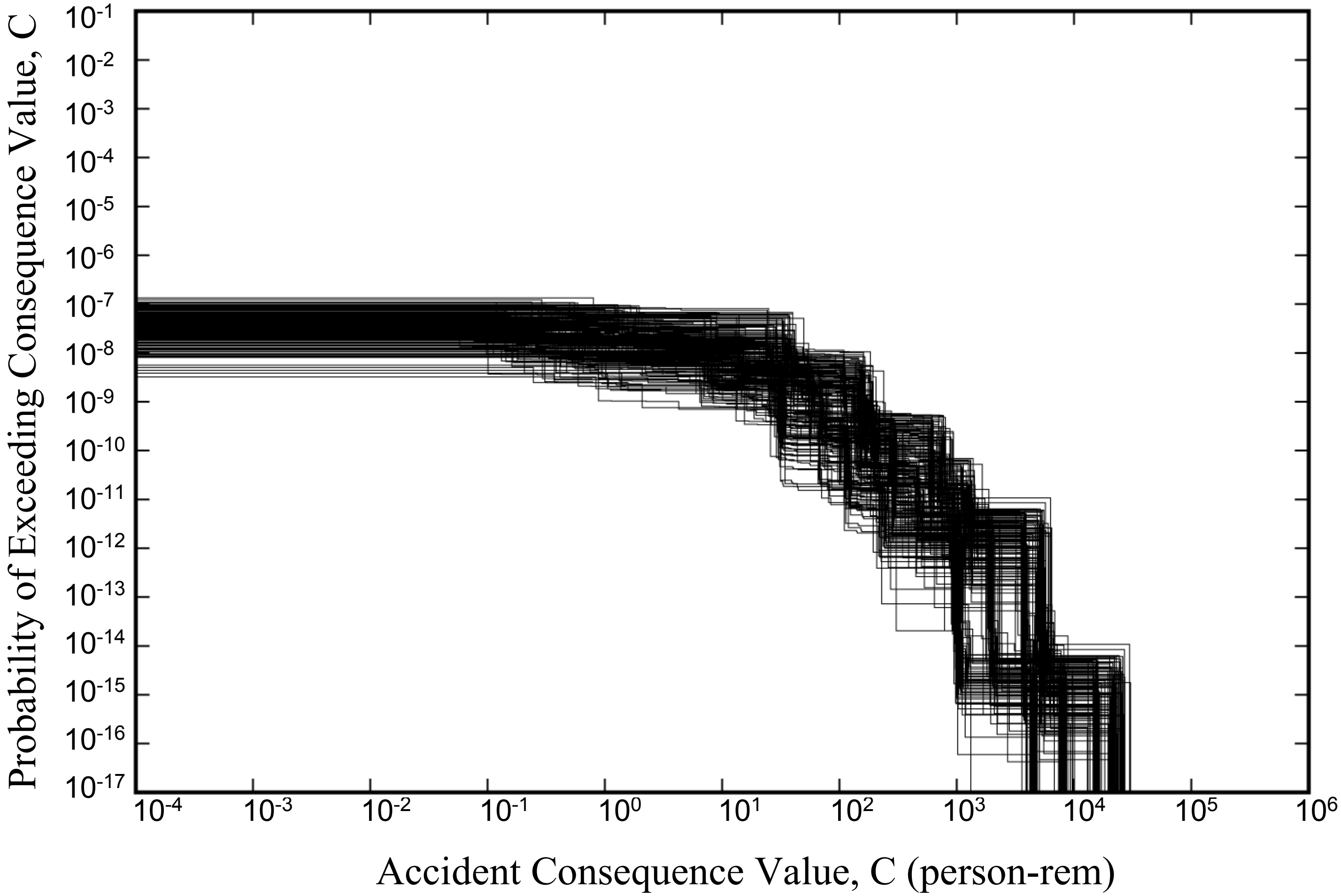

Figure 8.1 Two hundred truck accident population dose risk CCDFs, one CCDF for each representative truck route. Each RADTRAN 5 calculation examined all 19 representative truck accident source terms and assumed transport of PWR spent fuel in the generic steel-lead-steel truck cask.

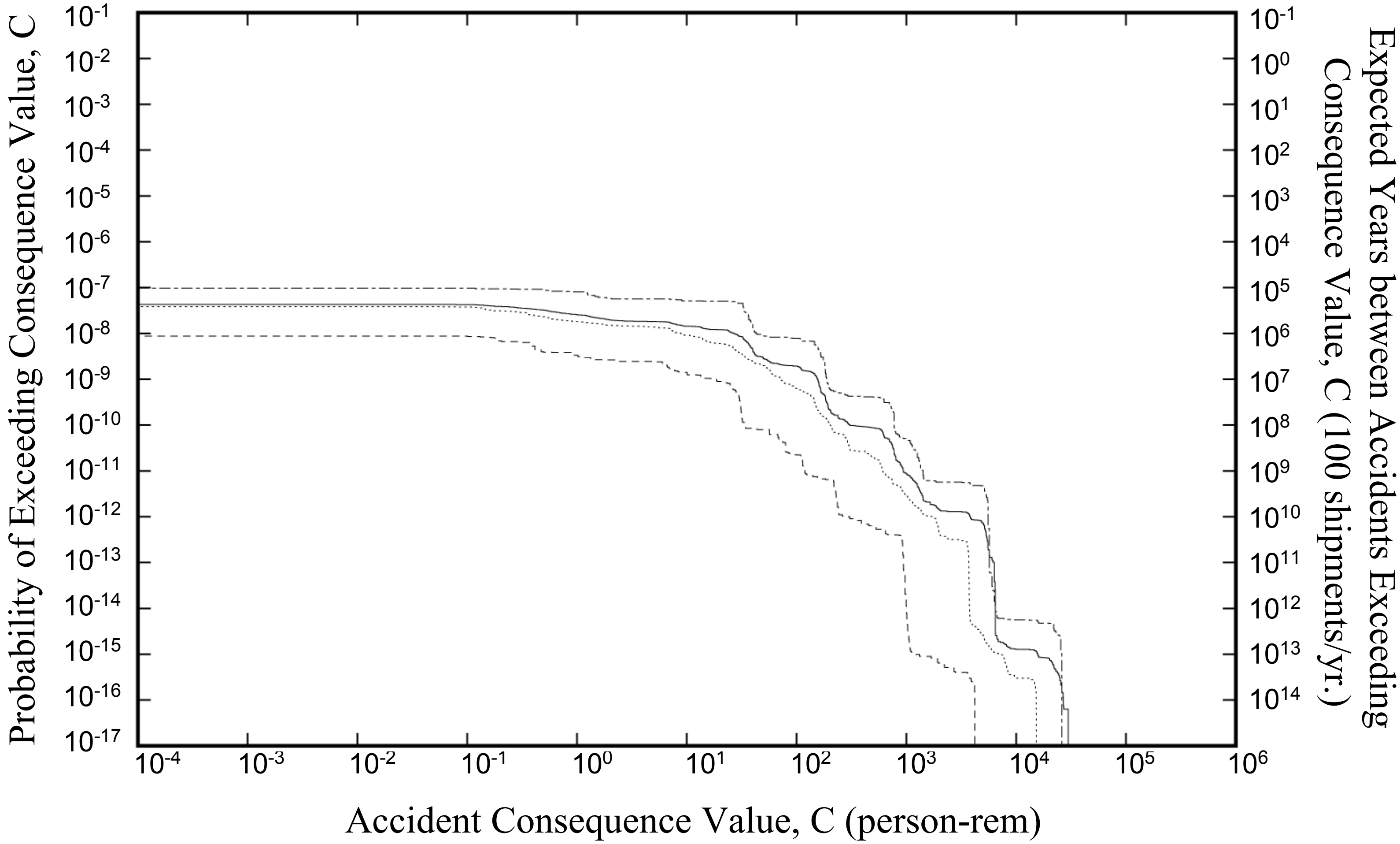

Figure 8.2 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the 200 representative truck routes. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (- - - - - - -) quantiles

parameters (e.g., segment length, segment population and segment vehicle densities, and average segment vehicle occupancy and speed), a type of prevailing weather (Pasquill-Gifford stability category), a package dose rate, a set of STOP parameter values, and the time after accident initiation when any evacuation of downwind population is completed. Because the LHS sample contained 200 sets of input data, the compound CCDF for the expected (mean) population dose is based on (derived from) $200 \times 45 = 9000$ cases (core calculations) that each examine one route segment, one prevailing weather, and one value for all of the other sampled parameters. Because the 15 source terms examined by this calculation are not specified in the LHS sample, the effect of the range of source term sizes on accident population dose is depicted by the curvature of each of the four compound CCDFs while the effects of the parameters that are varied within the LHS sample are depicted by the range (spread) of the four compound CCDFs at any single value of accident population dose.

The CCDF in Figure 8.2 and all subsequent CCDFs contain a second y-axis scale that was not present in the CCDF in Figure 8.1. That scale gives an estimate of the expected time between accidents that have consequences that exceed the corresponding x-axis value (consequences > C). Thus, an accident that has an expected time between accidents of 100 years would be expected on average to occur about once every 100 years, although there is a slight chance that two of these accidents could occur within a few years of each other. For example, inspection of the figure shows that an accident that produces a population dose that exceeds 1 rem is expected to occur about once every million years .

The values on the left-hand y-axis, the probability axis, are converted to those on the right-hand y-axis, the expected time between accidents axis, by taking the reciprocal of the product of the probability axis value and an estimate of the number spent fuel shipments likely to occur each year, i.e., years per accident = $[(\text{accidents per shipment})(\text{shipments per year})]^{-1}$. The following qualitative arguments allow an order-of-magnitude estimate of the number of spent fuel shipments per year to be developed.

An interim or permanent storage facility can probably receive at most a few casks per day or perhaps several hundred per year. The U.S. DOE has estimated [8-4] that during the first decade of spent fuel shipments, about 900 MTU will be shipped per year, which is equivalent to about 80 rail shipments per year. If 900 MTU are shipped per year by truck, about 1000 shipments per year would be needed; however, because rail is the preferred shipment mode, many fewer truck shipments are likely to be made per year. The entire spent fuel inventory can be shipped by rail over thirty years at a rate of about 200 shipments per year. Forty rail casks making a round-trip by regular freight once every two weeks can handle about 200 shipments per year. Therefore, because it is easy to scale (e.g., at 200 rather than 100 shipments per year, all of the right-hand y-axis values would be halved), an order-of-magnitude value of 100 shipments per year was used to convert the probability axis values to the values on the expected time between accidents axis.

Figures 8.3 through 8.5 respectively present sets of compound CCDFs for the generic steel-lead-steel truck cask carrying BWR spent fuel, for the generic steel-DU-steel truck cask carrying PWR spent fuel, and for the generic steel-DU-steel truck cask carrying BWR spent fuel, that are

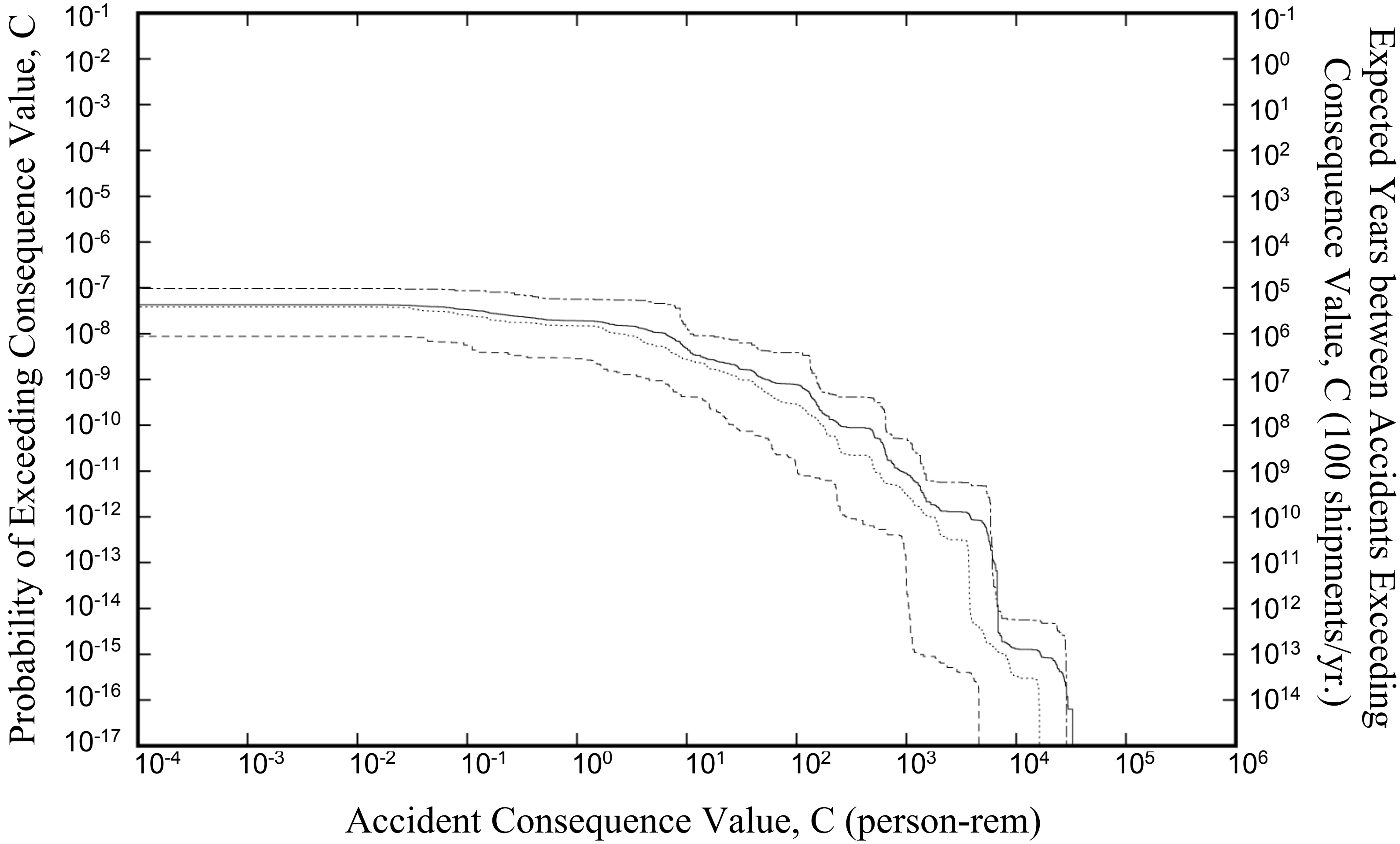

Figure 8.3 Truck accident population dose risk CCDFs for transport of BWR spent fuel in the generic steel-lead-steel truck cask over the 200 representative truck routes. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

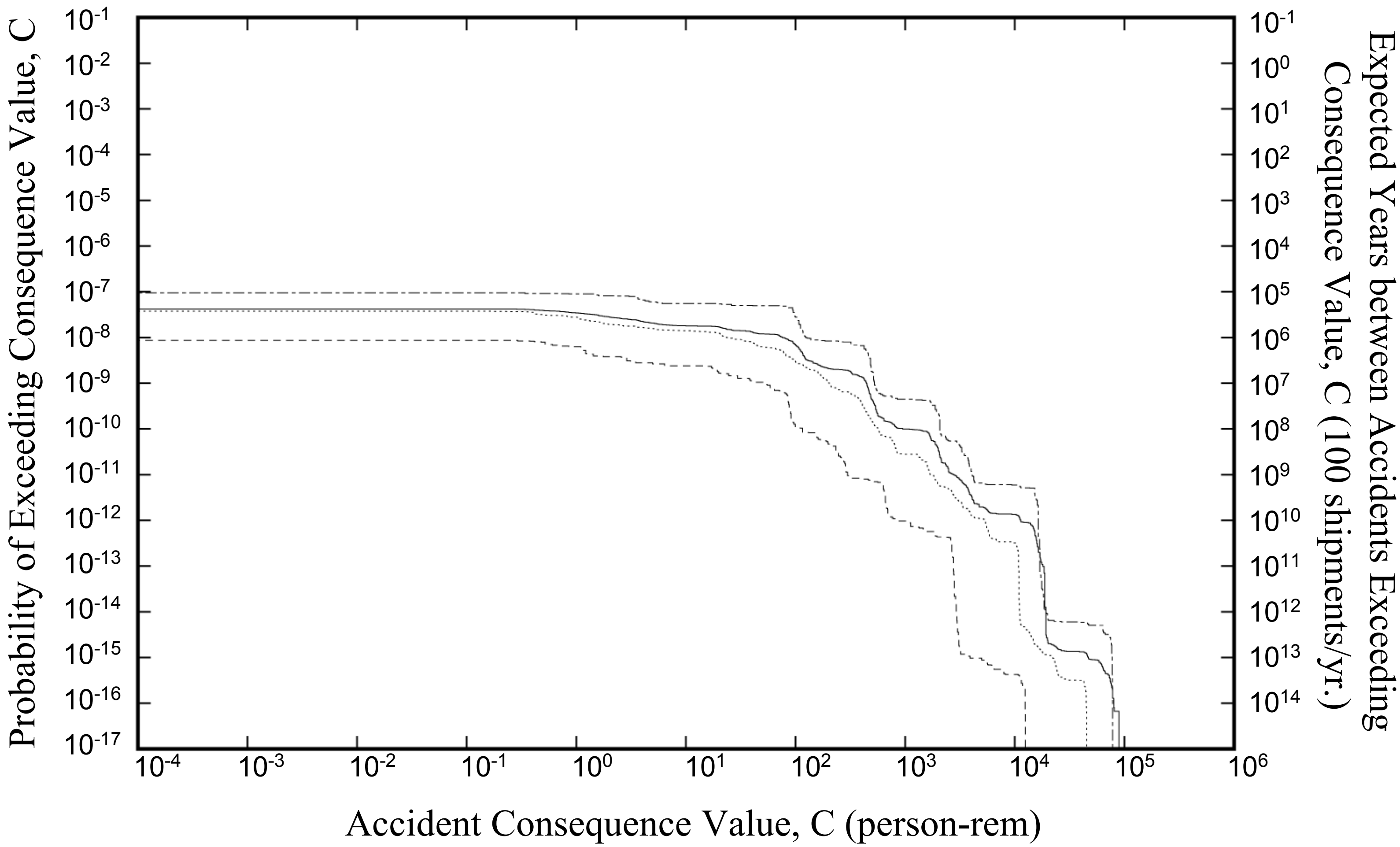

Figure 8.4 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-DU-steel truck cask over the 200 representative truck routes. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (————) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

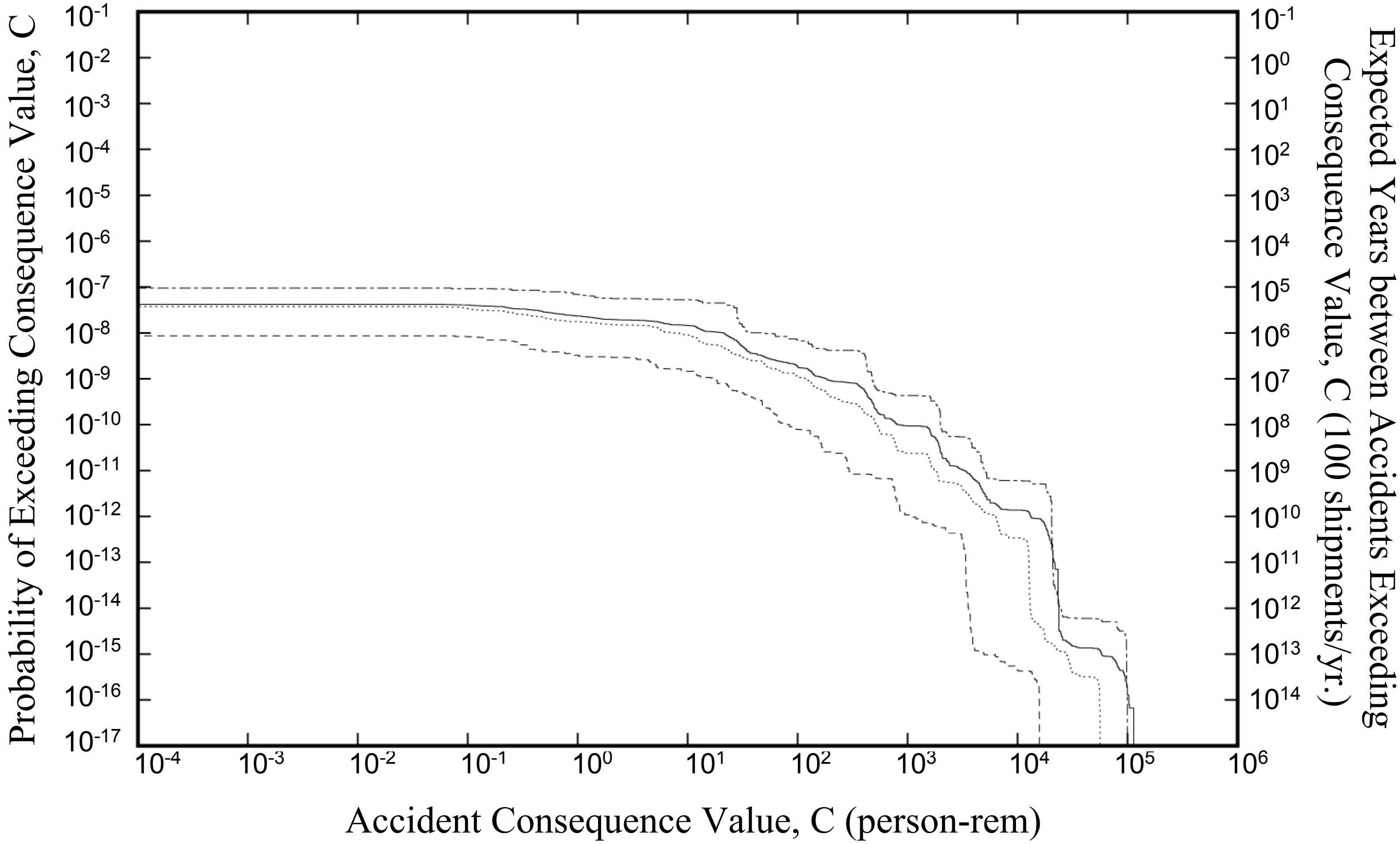

Figure 8.5 Truck accident population dose risk CCDFs for transport of BWR spent fuel in the generic steel-DU-steel truck cask over the 200 representative truck routes. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

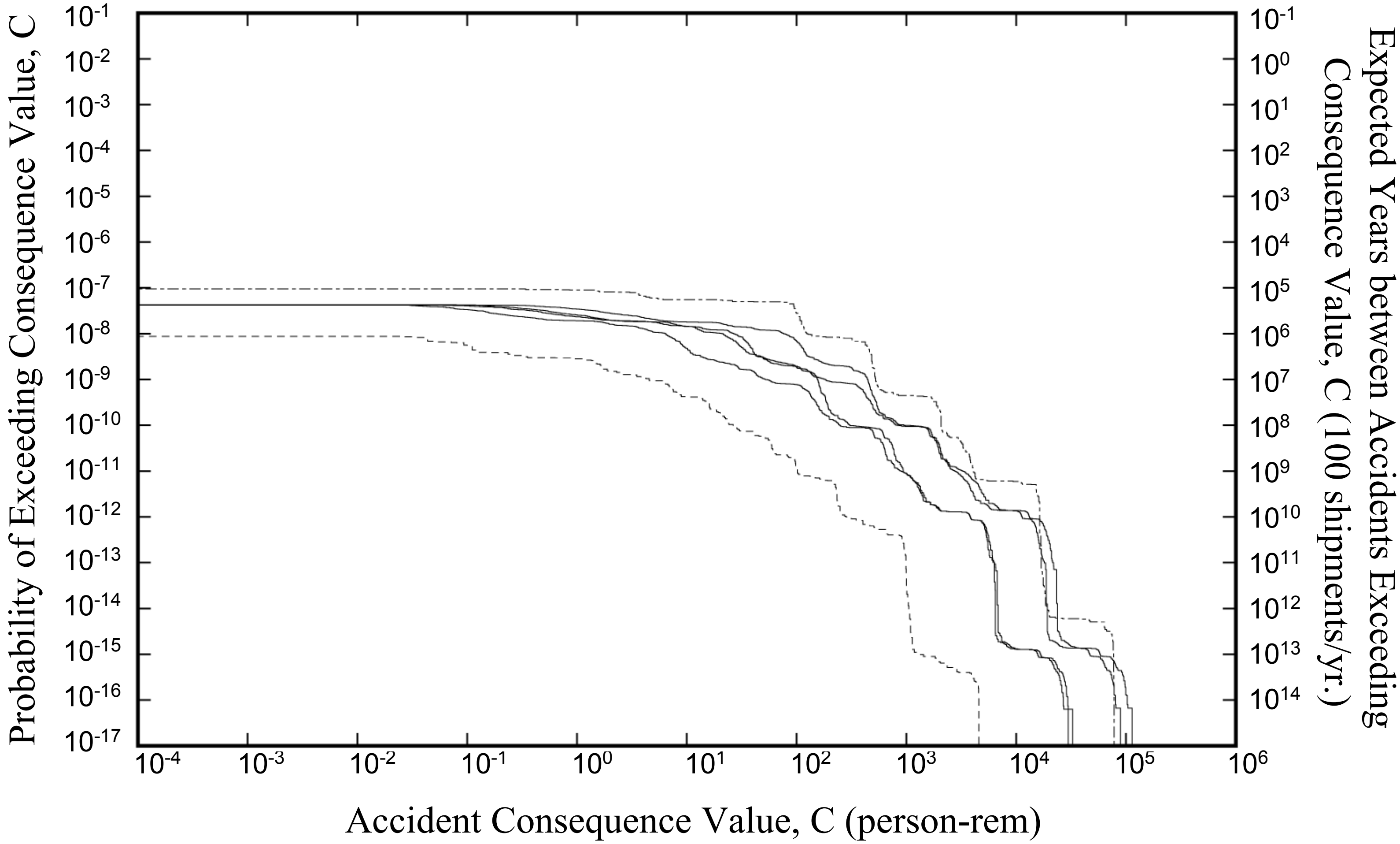

Figure 8.6 Comparison of truck accident population dose risk CCDFs for transport of PWR or BWR spent fuel in generic steel-lead-steel or steel-DU-steel truck casks over the 200 representative truck routes. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Four Mean CCDFs (———), and Highest 95th (-·-·-·-·-·) and Lowest 5th (----------) quantiles

exactly analogous to those presented in Figure 8.2. The expected (mean) CCDFs from Figures 8.2 through 8.5 and the highest 95th percentile and lowest 5th percentile CCDF in these four figures are plotted together in Figure 8.6. Thus, this figure depicts the likely range of truck accident population doses for accidents that are severe enough to cause a Type B spent fuel cask to lose containment and to fail some of the rods in the cask.

The area under the expected (mean) CCDF in Figures 8.2 through 8.5 is the expected value of truck accident population dose for the entire set of RADTRAN 5 spent fuel truck transport calculations performed for each generic truck cask and type of spent fuel. Table 8.4 presents these expected truck accident population doses and compares them to the expected (average) values of three incident-free population doses (stop, other, and total incident-free dose) that were developed by the same set of calculations. Because all incident-free doses have a probability of occurrence of one (i.e., if the spent fuel shipment is completed without an accident occurring, the estimated incident-free doses presented in Table 8.4 will be incurred), the value of any incident-free population dose is also the value of the corresponding incident-free population dose-risk, and the average of all of the values of any specific incident-free population dose is the expected (mean) value of that incident-free dose.

In Table 8.4, two values for Stop Dose are presented for each metric. The first value, the "Sleep" value, was calculated assuming that the one-person truck crew makes stops for inspections, to eat, to refuel, and to sleep. Because of these stops, on average the truck stops for 0.011 hour for each kilometer traveled [8-5], where this value was developed by surveying the types of stops and stop times made by typical commercial tractor semi-trailer trucks [8-5]. The second stop dose value, the "No Sleep" value, was calculated by dividing the first value, the "Sleep" value, by 28. This was done after phone calls to shippers of Hazardous materials [8-6] indicated that trucks transporting spent fuel casks have two-person crews, do not make sleep stops, and thus have a stop time per kilometer of travel much smaller than 0.011 hours per kilometer.

The phone calls [8-6] to shippers of Hazardous Material developed the following picture of the types of stops and stop times made by trucks transporting spent fuel casks. First, the 2-person crews of these trucks alternate driving on 4-hour shifts. During each 12-hour period, one driver drives for eight hours and sleeps for four hours and the other driver drives for four hours, sleeps for four hours, and rides as an escort for four hours. During the second 12-hour period in each day, this pattern is reversed. Two types of stops are made, food/refueling stops and inspection stops. Inspection stops are made every 100 miles or every two hours, whichever comes first. Since average truck speeds on interstate highways are greater than 50 mph, an inspection stop is made once every 100 miles, preferably at a truck stop, sometimes on a freeway exit ramp, or, if necessary, on the freeway shoulder. Regulations stipulate that the first inspection stop should be made after 25 miles of travel so that the cask tiedowns can be checked. Additional inspection stops are then made after each additional 100 miles of travel. After each 800 miles of travel, a stop is made for refueling and to eat or buy food. These stops may last as long as an hour, but typically take only 30 minutes. Because the inspections are "walk-around" inspections, they take at most 15 minutes and usually about 10 minutes. Thus, industry practice for spent fuel shipments under exclusive use conditions is to use two-man crews and to minimize stop time by not making stops to sleep.

Table 8.4 Incident-Free and Accident Population Dose Risks for Truck Transport

Metric	Population Dose Risks (person-rem)					
	Incident-Free					Accident
	Stops[a]		Other[b]	Total		
	Sleep[c]	No Sleep[d,e]		Sleep[c]	No Sleep[d]	
PWR Spent Fuel; Steel-Lead-Steel Cask; 1 Assembly						
Mean =	0.427	0.0153	0.0288	0.456	0.0441	8.00E-07
Standard Deviation =	0.296	0.0106	0.0238	0.297	0.0261	8.53E-07
Maximum =	1.840	0.0657	0.1340	1.974	0.1997	4.38E-06
Minimum =	0.017	0.0006	0.0024	0.019	0.0030	4.06E-08
PWR Spent Fuel; Steel-DU-Steel Cask; 3 Assemblies						
Mean =	0.427	0.0153	0.0288	0.456	0.0441	2.29E-06
Standard Deviation =	0.296	0.0106	0.0238	0.297	0.0261	2.44E-06
Maximum =	1.840	0.0657	0.1340	1.974	0.1997	1.24E-05
Minimum =	0.017	0.0006	0.0024	0.019	0.0030	1.14E-07
BWR Spent Fuel; Steel-Lead-Steel Cask; 2 Assemblies						
Mean =	0.427	0.0153	0.0288	0.456	0.0441	3.30E-07
Standard Deviation =	0.296	0.0106	0.0238	0.297	0.0261	3.61E-07
Maximum =	1.840	0.0657	0.1340	1.974	0.1997	1.99E-06
Minimum =	0.017	0.0006	0.0024	0.019	0.0030	1.68E-08
BWR Spent Fuel; Steel-DU-Steel Cask; 7 Assemblies						
Mean =	0.427	0.0153	0.0288	0.456	0.0441	1.08E-06
Standard Deviation =	0.296	0.0106	0.0238	0.297	0.0261	1.20E-06
Maximum =	1.840	0.0657	0.1340	1.974	0.1997	6.51E-06
Minimum =	0.017	0.0006	0.0024	0.019	0.0030	5.22E-08

a. Exposures at rest, food, and refueling stops.
b. Sum of on-link, off-link, and crew doses.
c. Sleep means that the truck makes a rest stop of 8 hours once every 24 hours so the crew can sleep.
d. No Sleep means that the truck doesn't make any rest stops to allow the crew to sleep.
e. The No Sleep stop dose is obtained by dividing the Sleep stop dose by 28.

The pattern of spent fuel shipment stops described above suggests that seven 10 minute inspection stops and one 30 minute food/refueling stop will be made during each 1280 kilometer = 800 mile portion of a truck spent fuel shipment. Thus, the total stop time for each 1280 kilometers of travel when no stops to sleep are made will be 1.67 hrs = [7(10 minutes) +1(30 minutes)]/60 minutes hr^{-1}.

The effect on stop doses of eliminating sleep stops is now developed for two spent fuel shipment routes. The first route, Crystal River to Hanford, is one of the four illustrative real routes examined below in Section 8.10, while the second route has route parameter values that are set to the means of the distributions of route parameter values that were used to construct the LHS sample of size 200. The lengths and urban, suburban, and rural length fractions and population densities of these two routes are given below in Table 8.7.

The stop model implemented in RADTRAN 5, the version of RADTRAN used in this study, calculates stop doses to people in two radial intervals centered on the stopped truck that is transporting the spent fuel cask, 1 to 10 m and 10 to 800 m. The population density of the first interval is assumed to be 30,000 people per square kilometer (0.03 people per square meter). The population density of the second interval is set equal to the average population density of the suburban portions of the route. No shielding is assumed for persons in the first interval. Because of intervening trucks and buildings, a shielding factor of 0.2 is assumed for persons in the second interval.

When stops to sleep are assumed to occur, the total stop time for the Crystal River-to-Hanford route, which has a length of 4818.5 km, is 53 hours = (4818.5 km)(0.011 hr km-1). Using this total stop time, RADTRAN predicts that the aggregate stop dose received by persons in these two intervals aggregated over all stops will be 0.128 person-rem to persons exposed in the first interval, the area immediately adjacent to the spent fuel truck, and 5.4×10^{-4} person-rem to other persons at the truck stop and residents of the area that immediately neighbors the truck stop.

An estimate of the stop doses that would result for the Crystal River-to-Hanford route if the route is traveled without making stops to sleep can be developed by scaling these two stop doses using scale factors that reflect (a) the smaller stop times incurred when stops to sleep are not made, (b) changes in the densities of the exposed populations, and (c) changes in the shielding factors that apply to each exposed population group. To do this let

D_1 = the dose to persons exposed in the first radial interval = 0.128 person-rem
D_2 = be the dose to persons exposed in the second radial interval = 5.4×10^{-4} person-rem
$f_{shielding}$ = the shielding factor assumed for persons in the second radial interval = 0.2
$t_{rest,sleep}$ = the stop time at rest stops when sleep stops are made = 53 hrs
$t_{rest,no\ sleep}$ = the stop time at rest stops when sleep stops are made = 1.9 hrs = 0.5 hrs (4818.5 km/1280 km)
$t_{inspections}$ = the time spent at inspection stops = 4.4 hrs = (70 min/60 min per hr)(4818.5 km/1280 km)
ρ_{rest} = the population density of the first radial interval = 3×10^4 persons/km^2
ρ_{urban} = the population density of urban portions of the Crystal River-top-Hanford route = 2190 persons/km^2
$\rho_{suburban}$ = the population density of suburban portions of the Crystal River-top-Hanford route = 331 persons/km^2
ρ_{rural} = the population density of rural portions of the Crystal River-top-Hanford route = 7.5 persons/km^2
f_{urban} = the urban length fraction of the Crystal River-top-Hanford route = 0.01
$f_{suburban}$ = the suburban length fraction of the Crystal River-top-Hanford route = 0.15
f_{rural} = the rural length fraction of the Crystal River-top-Hanford route = 0.84

Given these definitions, the population dose for transit of the Crystal River-to-Hanford route if no sleep stops are made is

$$\mathrm{Dose}_{\text{no sleep}} = \left(D_1 + D_2\right)\left(\frac{t_{\text{rest, no sleep}}}{t_{\text{rest,sleep}}}\right) + \left(D_1\left[\frac{\rho_{\text{suburban}}}{\rho_{\text{rest}}}\right] + D_2\left[\frac{1}{f_{\text{shielding}}}\right]\right)\left(\frac{t_{\text{inspections}}}{t_{\text{rest,sleep}}}\right)F_{\text{population}}$$

where

$$F_{population} = f_{urban}\left(\frac{\rho_{urban}}{\rho_{suburban}}\right) + f_{suburban}\left(\frac{\rho_{suburban}}{\rho_{suburban}}\right) + f_{rural}\left(\frac{\rho_{rural}}{\rho_{suburban}}\right)$$

In the first equation, the factor ($t_{rest,no\ sleep}/t_{rest,sleep}$) corrects $D_1 + D_2$, the rest stop dose for travel with sleep stops, for the decrease in time spent at rest stops when travel takes place without sleep stops; the factor ($\rho_{suburban}/\rho_{rest}$) adjusts D_1, the dose in the first radial interval, to the dose that would be received if the first radial interval had a suburban population density; the factor ($1/f_{shielding}$) corrects D_2, the dose received in the second radial interval, which is assumed to have a suburban population density, to the dose that would be received by the population of this interval if their shielding factor had a value of 1.0, the value used in RADTRAN for persons who are outdoors; and the factor ($t_{inspections}/t_{rest,sleep}$)$F_{population}$ = ($t_{inspections}/t_{rest,sleep}$)$\Sigma f_i\rho_i/\rho_{suburban}$, where i = urban, suburban, or rural, scales this adjusted rest stop dose for travel with sleep stops for the fraction of time spent at inspection stops in urban, suburban, and rural areas and also for the ratio of the population density of each of these regions to that of the suburban region, which is the reference population density for the adjusted rest stop dose.

Finally, substitution of the values for the parameters that enter these two equations into the equations yields $Dose_{no\ sleep} = 4.69 \times 10^{-3}$ person-rem (note that this value is essentially unchanged if the first radial interval at inspection stops is assumed to be devoid of population, which would likely be true for inspection stops conducted on freeway offramps or shoulders). Accordingly,

$$Dose_{sleep}/Dose_{no\ sleep} = (0.128 \text{ person-rem} + 5.4\text{x}10^{-4} \text{ person-rem})/4.69\text{x}10^{-3} \text{ person-rem} = 27.4$$

A nearly identical scale factor can be derived using the mean values of the distributions of route lengths and urban, suburban, and rural length fractions and population densities, that were sampled to produce the LHS sample of size 200. Thus, for an 800 mile = 1280 km portion of this route,

$$\frac{Dose_{sleep}}{Dose_{no\ sleep}} = \frac{(\text{person} - \text{hours})_{sleep}}{(\text{person} - \text{hours})_{no\ sleep}} = \frac{\rho_{rest}(1280\text{ km})(0.011\text{ hr km}^{-1})}{t_{inspection\ stop}\sum_i N_i\rho_i + t_{rest\ stop}\rho_{rest}}$$

where $t_{inspection\ stop}$ = 0.17 hr = 10 min/60 min, $t_{rest\ stop}$ = 0.5 hr = 30 mi/60 min, as before i = urban, suburban, or rural, N_i = the number of inspection stops in each portion of the route, and, given the fractions of the route length that are urban, suburban, and rural, $N_{urban} = 0$, $N_{suburban} = 2$, and $N_{rural} = 5$. Substitution of parameter values into this equation now yields

$$Dose_{sleep}/Dose_{no\ sleep} = 4.36\text{x}10^{5} \text{ person-hrs}/1.51\text{x}10^{4} \text{ person-hrs} = 28.9$$

Since the average of this value and the value for the Crystal River-to-Hanford route is 28.2, stop doses for travel without sleep stops was estimated by dividing the stop dose calculated by RADTRAN for travel with sleep stops by 28.

Table 8.4 shows that all four truck spent fuel transport calculations yield the same set of incident-free population doses. Each calculation yields the same set of incident-free doses because the incident-free portion of these calculations each used the same set of 200 routes and 200 cask dose rate values. Table 8.4 also shows (a) that incident-free population dose incurred at stops exceeds all other incident-free population doses by a factor of 15 if sleep stops are assumed to be taken, (b) that other incident-free doses exceed stop dose by about a factor of 2 if transport is assumed to occur without sleep stops, and (c) that for any combination of a cask and a type of spent fuel (e.g., the steel-lead-steel cask carrying PWR spent fuel) the expected value of the total incident-free population dose risk exceeds the expected value of the accident population dose risk by at least a factor of $2x10^4 = 0.0441/2.29x10^{-6}$, if no stops for sleep are taken, or as much as $1.4x10^6 = 0.456/3.3x10^{-7}$, were sleep stops to be taken. Thus, for any truck shipment, incident-free dose risks greatly exceed accident dose risks.

Division of the dose risk values presented in Table 8.4 by the number of assemblies that produced those dose risks shows that, on a per assembly basis, the expected accident population doses for PWR and BWR spent fuel are respectively about 7.8E-7 and 1.6E-7 person-rem. Thus, the expected accident population dose per assembly for truck transport of PWR spent fuel is about 5 times greater than that for BWR spent fuel, which was to be expected because the rod failure fractions for PWR spent fuel during accidents are about twice those of BWR spent fuel and the curie amounts of those radionuclides that drive population dose in three-year cooled, high-burnup PWR assemblies are about three times greater than those for three-year cooled, high-burnup BWR assemblies.

8.7 Results for the Generic Steel-Lead-Steel and Monolithic Steel Rail Casks

Figures 8.7 through 8.11 and Table 8.5 present for the generic steel-lead-steel and monolithic steel rail casks the same set of results that were developed for the generic truck casks. Figures 8.7 through 8.10 present the CCDFs of expected, 95^{th}, median, and 5^{th} percentile values of accident population dose that were calculated for each generic rail cask using first a PWR and then a BWR cask inventory. Figure 8.11 plots the four expected value CCDFs and compares them to the highest lying 95^{th} and the lowest lying 5^{th} percentile CCDF found in Figures 8.7, 8.8, 8.9, or 8.10. Thus, this figure depicts the likely range of rail accident population doses for accidents that are sufficiently severe to fail a Type B spent fuel rail cask and at least some of the rods in the cask.

Table 8.5 compares the expected values of incident-free population doses to the expected value of the corresponding accident population dose. Table 8.5 shows that, as was true for truck transport, each of the four spent fuel rail transport calculations yields the same set of incident-free doses (again because each calculation uses the same set of routes and cask dose rate values) and that the value of total incident-free rail transport population dose risk again greatly exceeds (by factors of approximately 10^3 to 10^4) the four values of rail transport accident population dose risk. However, in contrast to the result obtained for truck transport, other rail incident-free doses are larger than rail incident-free stop doses (by a factor of 3.6) because in general rail stops expose fewer people to radiation than truck stops, e.g., there are more people at truck rest stops and they are closer to the spent fuel cask and less shielded than at rail classification yards.

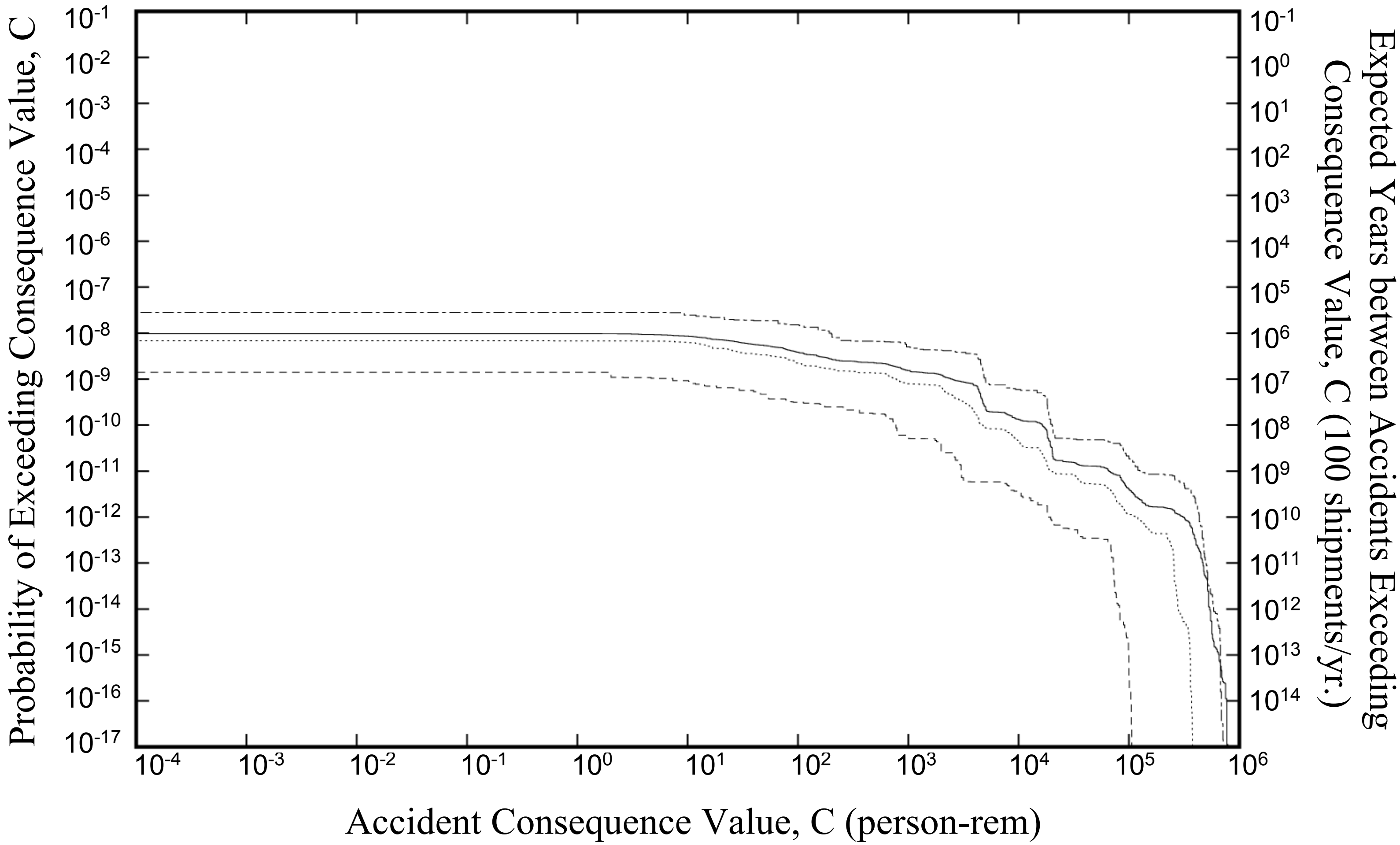

Figure 8.7 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel rail cask over the 200 representative rail routes. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (----------) quantiles

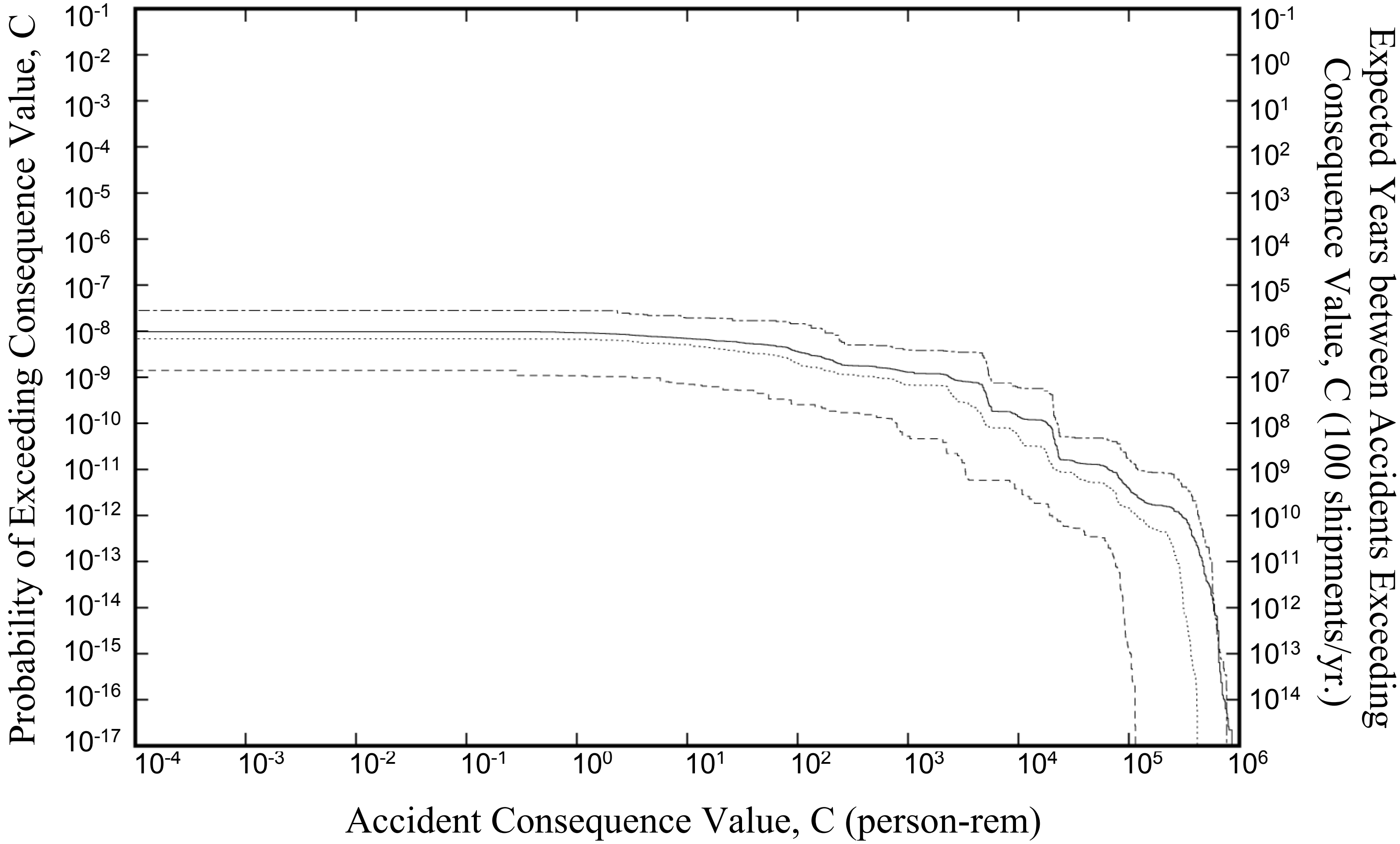

Figure 8.8 Rail accident population dose risk CCDFs for transport of BWR spent fuel in the generic steel-lead-steel rail cask over the 200 representative rail routes. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

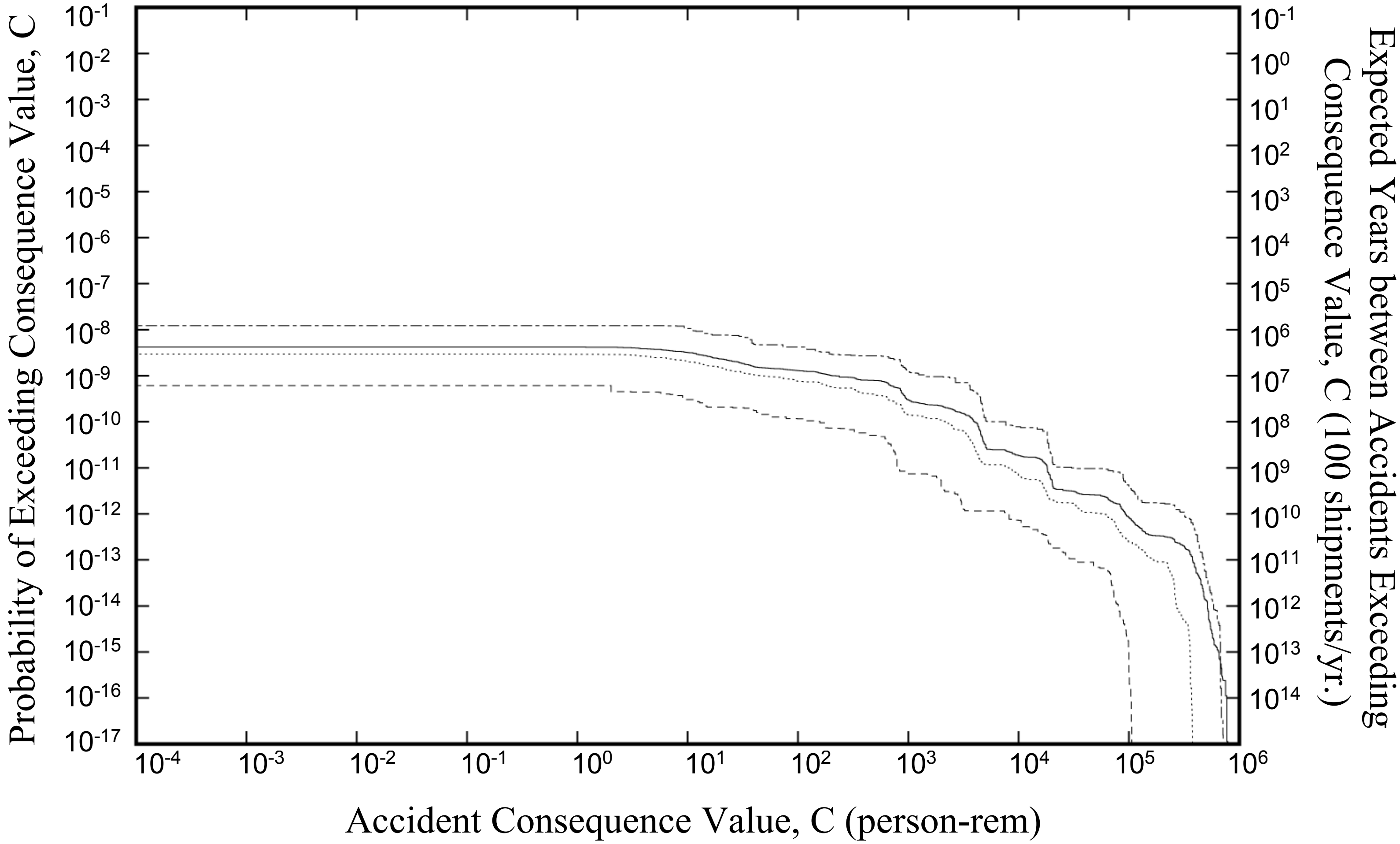

Figure 8.9 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the 200 representative rail routes. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

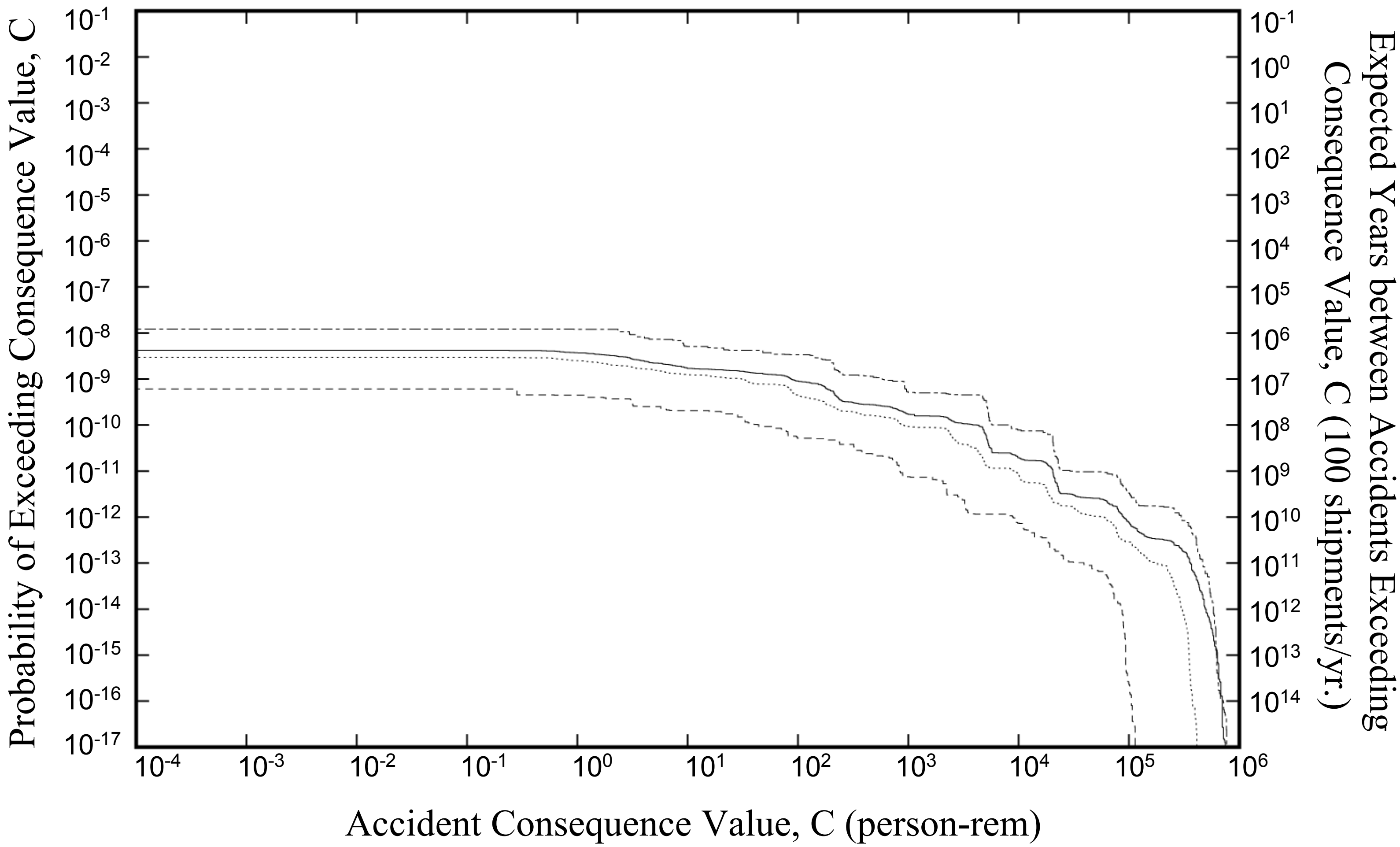

Figure 8.10 Rail accident population dose risk CCDFs for transport of BWR spent fuel in the generic monolithic steel rail cask over the 200 representative rail routes. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

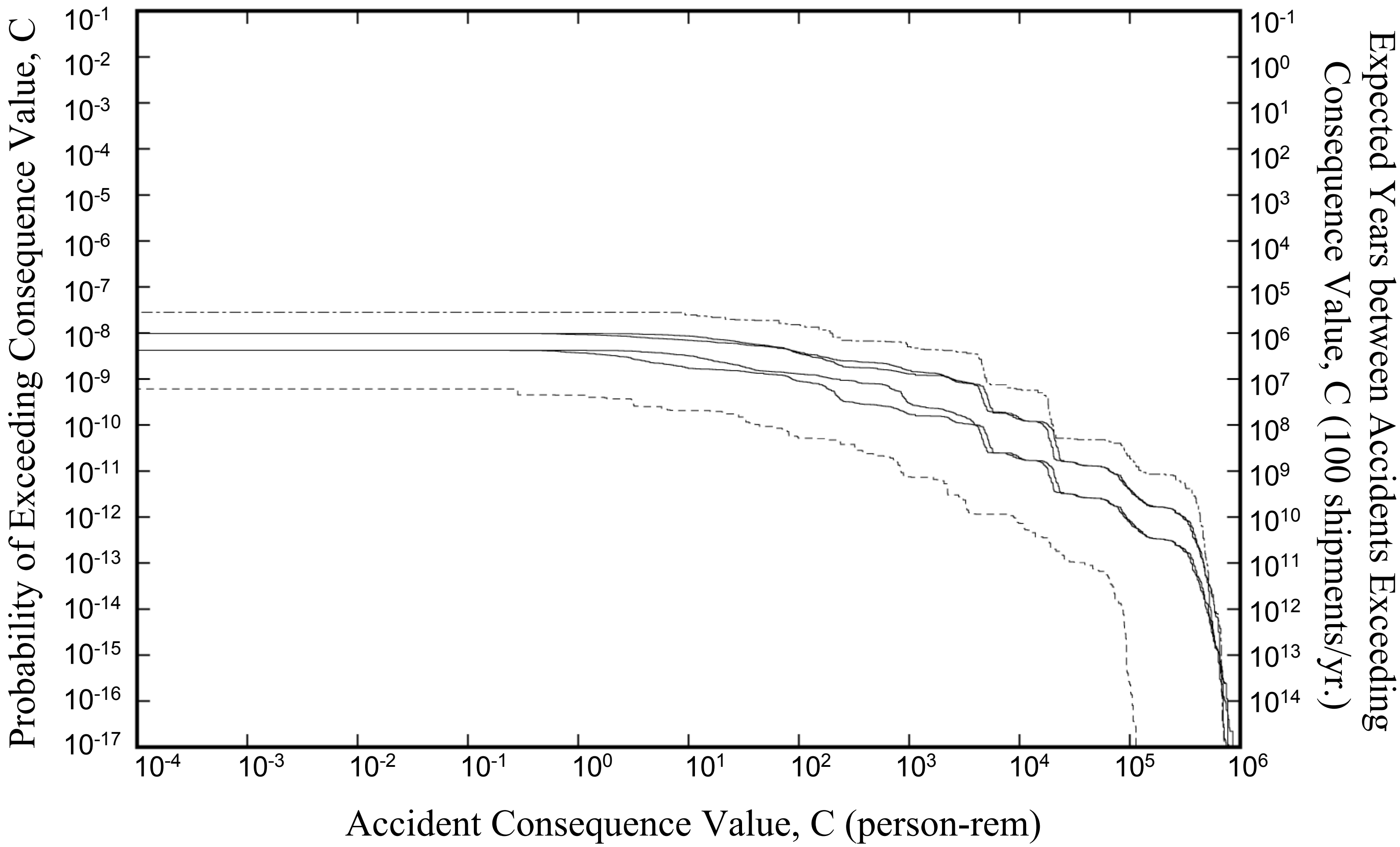

Figure 8.11 Comparison of rail accident population dose risk CCDFs for transport of PWR or BWR spent fuel in generic steel-lead-steel or monolithic steel rail casks over the 200 representative rail routes. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Four Mean CCDFs (———), and Highest 95th (-·-·-·-·-) and Lowest 5th (---------) quantiles

Table 8.5 Incident-Free Population Dose Risks for Rail Transport

Metric	Population Dose Risks (person-rem)			
	Incident-Free			Accident
	Stops[a]	Other[b]	Total	
PWR Spent Fuel; Steel-Lead-Steel Cask; 24 Assembly				
Mean =	4.37E-03	1.59E-02	2.03E-02	9.43E-06
Standard Deviation =	2.58E-03	1.38E-02	1.40E-02	1.18E-05
Maximum =	1.29E-02	8.26E-02	9.55E-02	6.32E-05
Minimum =	1.73E-03	3.57E-04	2.08E-03	3.39E-08
PWR Spent Fuel; Monolithic Steel Cask; 24 Assemblies				
Mean =	4.37E-03	1.59E-02	2.03E-02	1.99E-06
Standard Deviation =	2.58E-03	1.38E-02	1.40E-02	2.47E-06
Maximum =	1.29E-02	8.26E-02	9.55E-02	1.35E-05
Minimum =	1.73E-03	3.57E-04	2.08E-03	8.08E-09
BWR Spent Fuel; Steel-Lead-Steel Cask; 52 Assemblies				
Mean =	4.37E-03	1.59E-02	2.03E-02	9.23E-06
Standard Deviation =	2.58E-03	1.38E-02	1.40E-02	1.18E-05
Maximum =	1.29E-02	8.26E-02	9.55E-02	6.19E-05
Minimum =	1.73E-03	3.57E-04	2.08E-03	2.97E-08
BWR Spent Fuel; Monolithic Cask; 52 Assemblies				
Mean =	4.37E-03	1.59E-02	2.03E-02	1.46E-06
Standard Deviation =	2.58E-03	1.38E-02	1.40E-02	1.86E-06
Maximum =	1.29E-02	8.26E-02	9.55E-02	9.94E-06
Minimum =	1.73E-03	3.57E-04	2.08E-03	4.87E-09

a. Exposures at rest and refueling stops.
b. Sum of on-link, off-link, and crew doses.

Table 8.5 also shows that when shipped in the same cask, the expected accident population dose risk per assembly for shipping PWR spent fuel exceeds that for BWR spent fuel by factors of about 2 to 3. This ratio is smaller than what might have been expected given that rod failure fractions for PWR spent fuel during accidents are about twice those of BWR spent fuel and the curie amounts of those radionuclides that drive population dose in three-year cooled, high-burnup PWR assemblies are about three times greater than those for three-year cooled, high-burnup BWR assemblies.

8.8 Comparison of Truck and Rail Transport Mean Risks

Comparison of the incident-free doses (incident-free risks and incident-free doses are the same because the probability of occurrence of the incident-free dose is unity) presented in Tables 8.4 and 8.5 shows that, for shipment of a single truck or train spent fuel cask, truck stop doses exceed train stop doses by a factor of 100, if trucks make sleep stops, and by a factor of 35, if truck sleep stops are not taken; other truck doses exceed other train doses by only a factor of two; and total truck incident-free doses exceed total train incident-free doses by a factor of 22.5, if truck sleep stops are made, and by a factor of 2, if trucks do not make sleep stops. Other truck and other train doses are similar because truck and train spent fuel casks, when undamaged, have similar surface dose rates, so people who reside by the route or are traveling on the route, when the cask passes by, receive similar radiation exposures. Even though rail casks carry many more fuel assemblies than are carried by truck casks, truck and train cask surface dose rates are similar because in rail casks, inner assemblies are shielded by outer assemblies and because cask surface dose rates are limited by regulation. However, because typical truck casks carry either 1 or 3 PWR assemblies or 2 or 7 BWR assemblies, while typical rail casks carry 24 PWR or 52 BWR assemblies, it will take at least $8 = 24/3$ and possibly $24 = 24/1$ times as many truck shipments as train shipments to transport any given quantity of PWR spent fuel, and at least $7.4 = 52/7$ and possibly $26 = 52/2$ times as many truck shipments as train shipment to transport a given quantity of BWR spent fuel. Therefore, on a campaign basis, truck incident-free doses might be expected to exceed rail incident-free doses by factors of about $180 = 8 \times 22.5$ to $585 = 26 \times 22.5$. Although this factor seems large, it is really of no concern, since all individual incident-free doses will be within regulatory limits and also small when compared to normal yearly background radiation doses.

Because truck casks carry fewer assemblies than rail casks, should a truck cask and a rail cask both be involved in accidents that inflict the same damage on both casks (i.e., both accidents fail the same fraction of the rods in each cask and both fail each cask in the same way, e.g., seal failures of the same size), the overall impact from a train accident would be expected to be larger because the radioactive release from the rail cask would be larger than that from the truck cask. Comparison of Tables 8.4 and 8.5 shows that, depending on the casks used, mean train accident dose risks are either about the same as or about ten times greater than mean truck accident dose risks. Because, for any shipment campaign, transport by truck will require 8 to 26 more shipments than transport by rail on a campaign basis, truck accident dose risks will exceed train accident dose risks by factors of at least $8 = 8 \times 1$ and possibly as much as $260 = 26 \times 10$.

8.9 Comparison of NUREG-0170 Incident-Free Doses to Those of This Study

NUREG-0170 [8-1] developed estimates of incident-free doses for eight population groups: passengers, crew, attendants (e.g., flight attendants), handlers, population that resides along the route (off-link population), persons traveling on the route (on-link population), persons exposed at stops, and persons exposed at en route storage locations. For transport by truck or freight train, there are no passenger or attendant doses. Storage doses and handler doses were not examined during this study. Storage doses were not examined because direct shipment from the reactor to the temporary or permanent storage site without storage at any intermediate location was assumed. Handler doses were not examined because the doses incurred by workers loading the spent fuel cask at the reactor site and unloading the spent fuel cask at the temporary or permanent storage site are treated by most recent National Environmental Policy Act analyses as facility doses, not transportation doses. Therefore, incident-free doses were limited to those doses incurred while en route.

Table 8.6 compares the NUREG-0170 expected incident-free truck and rail doses presented in Table 1.2 to the expected incident-free doses presented in Tables 8.4 and 8.5 that were developed by this study. Because the NUREG-0170 doses were developed for all of the spent fuel shipments expected to occur in 1975 or 1985, doses for single shipments are calculated by dividing the 1975 or 1985 doses by the number of spent fuel shipments that NUREG-0170 [8-1] estimated would occur during these years.

Table 8.6 Comparison of NUREG-0170 Incident-Free Doses to the Incident-Free Doses Developed by this Study

Mode	Truck			Rail		
Study	**NUREG-0170**		**This Study**	**NUREG-0170**		**This Study**
Year	1975	1985		1975	1985	
Number of Shipments	254	1530	2489[a]	17	652	100.5[a]
	Expected Dose (person-rem)					
Multiple Shipments						
Handlers + Storage	52.06	313.6	Not Calc.	7.227	277.4	Not Calc.
Stops	4.82	29.0	38	0.089	3.440	0.442
Other[b]	36.92	222.4	72	0.464	17.16	1.598
Stops + Other	41.74	251.4	110	0.553	20.60	2.040
Single Shipment						
Handlers + Storage	0.205	0.205	Not Calc.	0.425	0.425	Not Calc.
Stops	0.0190	0.0190	0.0153[c]	0.0052	0.0053	0.0044
Other[b]	0.145	0.145	0.0288	0.02729	0.02632	0.0159
Stops + Other	0.164	0.164	0.0441	0.0325	0.0316	0.0203

a. Average number of shipments per year required to ship the full 1994 spent fuel inventory over 30 years in steel-lead-steel truck and rail casks.
b. Sum of crew, on-link, and off-link doses.
c. Result for truck shipments that proceed without taking sleep stops.

Table 8.6 shows that for truck transport the single shipment incident-free other doses (i.e., crew, on-link, and off-link doses) calculated for NUREG-0170 are about 5 times larger than those calculated for this study, that the single shipment incident-free stop doses calculated for NUREG-0170 are about 25 percent larger than those calculated for this study, and thus the single shipment total incident-free doses calculated for NUREG-0170 are about 3.7 times those calculated for this study. NUREG-0170 other doses exceed those calculated by this study by a factor of five because the average population density over the entire NUREG-0170 truck route exceeds the average population density of the set of 200 truck routes examined by this study by about a factor of 2.5 and the NUREG-0170 spent fuel cask surface dose rate is about twice the mean of the surface dose rate distribution used in this study.

The fact that NUREG-0170 truck stop doses exceed those developed by this study by 25 percent can be qualitatively explained as follows. Truck stop doses, D_{stop}, are proportional to the product of the cask surface dose rate, the population density at the truck stop, ρ_{pop}, the exposure time of that population, Δt, and the following slowly varying function of radial distance, f(r), that expresses the variation of radiation intensity with distance over the annular area of interest:

$$f(r) = \int_a^b 2\pi r \frac{e^{-\mu r} B(r)}{r^2} dr$$

where μ is the absorption coefficient for radiation by air and B(r) is the Berger buildup factor in air. When stops are made at locations that have different population densities, for example, urban, suburban, and rural rest stops, D_{stop} is proportional to the product of the cask dose rate, f(r), and $\Sigma(\Delta t\rho_{pop})_i$, where Δt and ρ_{pop} are the exposure time and the population density that characterize each stop made on the route.

The NUREG-0170 value for f(r) differs from the value used in this study because different integration limits are used for the function. For NUREG-0170, f(r) is evaluated from 3 to 800 meters and that annulus is assumed to have a population density that is the same as the population density of the urban, suburban, or rural region in which the stop is made. For this study, stop doses are evaluated over two concentric annuli with inner and outer radii of 1 and 10 meters and 10 and 800 meters. Because the population density of the inner annulus is taken to be 0.03 persons per square meter ($3x10^4$ persons per square kilometer) while the population density of the outer annulus is assumed to be that of a suburban route segment, the dose accumulated in the inner annulus dominates the stop dose. Therefore, the integration limits for f(r) for the calculations performed for this study are effectively 1 and 10 meters.

Since the values of TI, f(r), and $\Sigma(\Delta t\rho_{pop})_i$ are respectively 9.5, 27.3, and $1.1x10^4$ where

$$1.1x10^4 = (\Delta t\rho_{pop})_{urban\ stops} + (\Delta t\rho_{pop})_{suburban\ stops} + (\Delta t\rho_{pop})_{rural\ stops}$$

$$= (2\ hr)(3861\ km^{-2}) + (5\ hr)(719\ km^{-2}) + (1\ hr)(6.0\ km^{-2})$$

when NUREG-0170 data is used, and 4.5, 14.2, and $3x10^4$ where

$$3x10^4 = \Delta t\ \rho_{1\text{-}10\ m} = (1\ hr)(3x10^4\ km^{-2})$$

when data from this study is used, the ratio of NUREG-0170 truck stop doses to those estimated by this study should be approximately $1.49 = [(9.5)(1.1x10^4)(27.3)/[(4.5)(3x10^4)(14.2)]$, which is in reasonable agreement with the actual ratio of 1.25.

Table 8.6 also shows that the NUREG-0170 single shipment incident-free stop and other doses for transport by rail are larger than the corresponding doses calculated by this study by factors of 1.2 = 0.0052/0.0044 and 1.7 = 0.0263/0.0159, and therefore, NUREG-0170 total rail incident-free doses exceed those calculated for this study by about a factor of 1.6 = 0.0316/0.0203. The fact that the NUREG-0170 other incident-free rail doses exceed by a factor of 1.7 those calculated for this study is explained as follows. Other incident-free population dose is proportional the product of the cask dose rate and $\Sigma(\Delta t\ \rho_{pop})_i$ where $\Delta t = Lf_i/v_i$, L is the route length, f_i is the fraction of the length that is urban, suburban, or rural, and v_i is the train speed in these regions. Substitution of the values of these parameters used for the NUREG-0170 calculations and the means of the distributions of values used for the calculations performed for this study yields, in good agreement with the actual result, an estimate of 1.8 for this dose ratio, where

$$1.8 = \frac{D_{\text{other incident-free, NUREG-0170}}}{D_{\text{other incident-free, this study}}}$$

$$= \frac{\left[(\text{TI})(\text{L})\sum_{i}\frac{f_i}{v_i}\rho_i\right]_{\text{NUREG}-0170}}{\left[(\text{TI})(\text{L})\sum_{i}\frac{f_i}{v_i}\rho_i\right]_{\text{this study}}} = \frac{9.5(1210)\left[\frac{0.9}{64}(6)+\frac{0.05}{40}(719)+\frac{0.05}{24}(3861)\right]}{4.5(2560)\left[\frac{0.75}{64}(9.6)+\frac{0.22}{40}(356)+\frac{0.03}{24}(2280)\right]}$$

8.10 Illustrative Real Routes

All of the results presented in Sections 8.6 and 8.7 were calculated using 200 sets of RADTRAN 5 input (an LHS sample of size 200) that contains data for 200 different representative truck or rail routes, none of which exactly matches any real truck or rail route located in the continental United States. In this section, results for four illustrative real truck or rail routes and also for the NUREG-0170 representative truck or rail route are compared to the results developed using the 200 representative truck or rail routes embedded in the LHS samples that provided the input for the calculations described in Sections 8.6 and 8.7. All of the truck calculations examined transport of spent high-burnup PWR fuel in the generic steel-lead-steel truck cask, and all of the rail calculations examined transport of spent high-burnup PWR fuel in the generic monolithic steel rail cask.

Table 8.7 presents route parameter values for the four illustrative real truck and rail routes and also for the NUREG-0170 representative truck and rail routes that were examined by this set of RADTRAN 5 calculations. Also presented in the table are the mean values of the distributions of route parameters that were sampled in order to construct the 200 representative routes that were examined by the calculations described in Sections 8.6 and 8.7.

The four illustrative routes were chosen for the following reasons. The truck and rail routes from the Crystal River nuclear plant to Hanford are about the longest routes possible in the continental United States. Because they traverse the Boston-Washington urban corridor, the routes from the Maine Yankee nuclear plant to the Savannah River Site have urban length fractions and population densities that are about as high as is possible in the continental United States. The routes from the Maine Yankee nuclear plant to Skull Valley represent long routes to the Yucca Mountain area that traverse the urban Midwest. Finally, as Table 8.7 shows, the routes from the Kewaunee nuclear plant to the Savannah River Site have route parameter values (especially the urban parameter values) similar to the means of the route parameter distributions used to construct the 200 representative truck and rail routes contained in the LHS sample of size 200.

Table 8.7 NUREG-0170 and Illustrative Real Truck and Rail Routes

Origin	Destination	Length (km)	Fraction of Total Length			Population Density[a]			Stop Time[b]
			Rural	Suburban	Urban	Rural	Suburban	Urban	
Truck Routes									
Crystal River, FL	Hanford Site, WA	4818.5	0.84	0.15	0.01	7.5	331	2190	53.0
Maine Yankee, ME	Skull Valley, UT	4228.7	0.74	0.24	0.02	9.2	296	2286	46.5
Maine Yankee, ME	Savannah River Site, SC	1917.5	0.52	0.43	0.05	18.3	282	2565	21.0
Kewaunee, WI	Savannah River Site, SC	1765.0	0.63	0.32	0.05	16.3	358	2452	19.4
NUREG-0170		2530.0	0.90	0.05	0.05	6.0	719	3861	8.0
Route Parameter Distribution Mean Values		2550.0	0.76	0.23	0.01	10.1	336	2195	28.0
Rail Routes									
Crystal River, FL	Hanford Site, WA	5178.6	0.83	0.15	0.02	7.9	360	2063	231
Maine Yankee, ME	Skull Valley, UT	4488.7	0.75	0.22	0.03	8.9	337	2429	208
Maine Yankee, ME	Savannah River Site, SC	2252.7	0.52	0.38	0.10	14.3	325	2738	134
Kewaunee, WI	Savannah River Site, SC	1917.2	0.64	0.32	0.04	14.1	351	2268	122
NUREG-0170		1210.0	0.90	0.05	0.05	6.0	719	3861	24
Route Parameter Distribution Mean Values		2560.0	0.75	0.22	0.03	9.6	356	2280	144

a. People per square kilometer.
b. Sum of all stop durations (hours) for the entire shipment. For truck shipments, includes stop time for sleep stops.

8.10.1 Steel-Lead-Steel Truck Cask Results for Illustrative Routes

Figures 8.12 through 8.17 present the accident population dose risk and Table 8.8 presents the incident-free population dose risk results of the RADTRAN 5 calculations that examined spent fuel transport in the generic steel-lead-steel truck cask over the four illustrative truck routes and the NUREG-0170 truck route. Figures 8.12 through 8.15 present the results obtained for the four illustrative real truck routes, and Figure 8.16 presents the results obtained for the NUREG-0170 truck route. Each of these figures presents CCDFs of the expected, 95th, median, and 5th percentile values of accident population dose risks that were calculated for the generic steel-lead-steel truck cask carrying spent PWR high-burnup fuel along the indicated illustrative real truck route or along the NUREG-0170 representative truck route. In Figure 8.17, the mean (expected) CCDFs from each of these calculations are plotted together and compared to the 5th and 95th percentile CCDFs depicted in Figure 8.6. Thus, Figure 8.17 compares the expected accident population dose risks for the illustrative truck and NUREG-0170 truck route calculations to the range of the accident population dose risks developed using the 200 representative truck routes that were constructed by LHS sampling from truck route parameter distributions. Comparison of Figure 8.17 to Figures 8.12 through 8.16 shows (a) that the CCDFs for the four illustrative truck routes are quite similar, (b) that they all lie below the CCDF of 95th percentile values for the LHS calculations that examined the 200 representative truck routes, and (c) that the CCDF for the NUREG-0170 truck route calculation lies below the four illustrative truck route CCDFs when accident population dose risks are below 100 person-rem but then crosses these CCDFs and

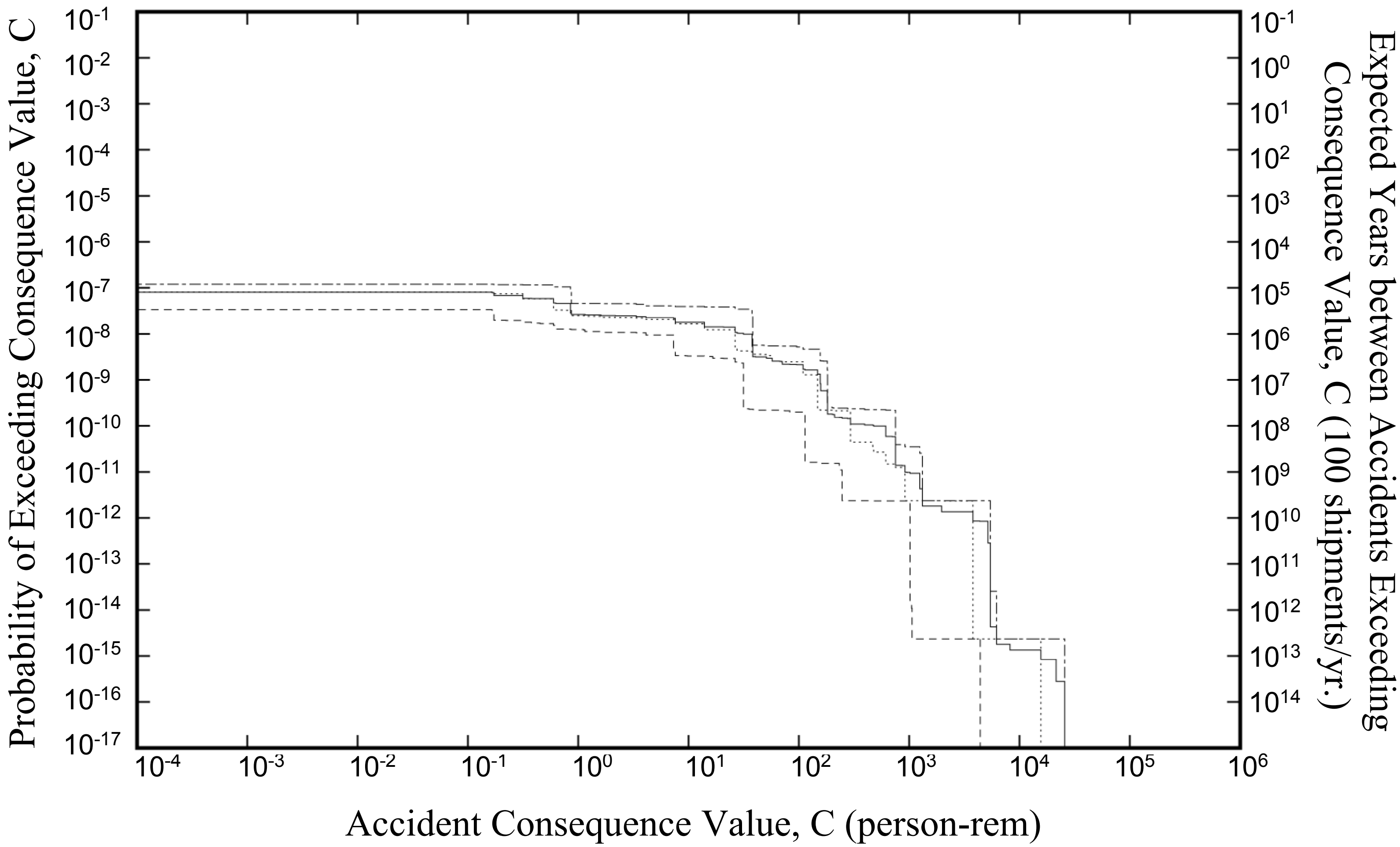

Figure 8.12 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the Crystal River to Hanford illustrative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

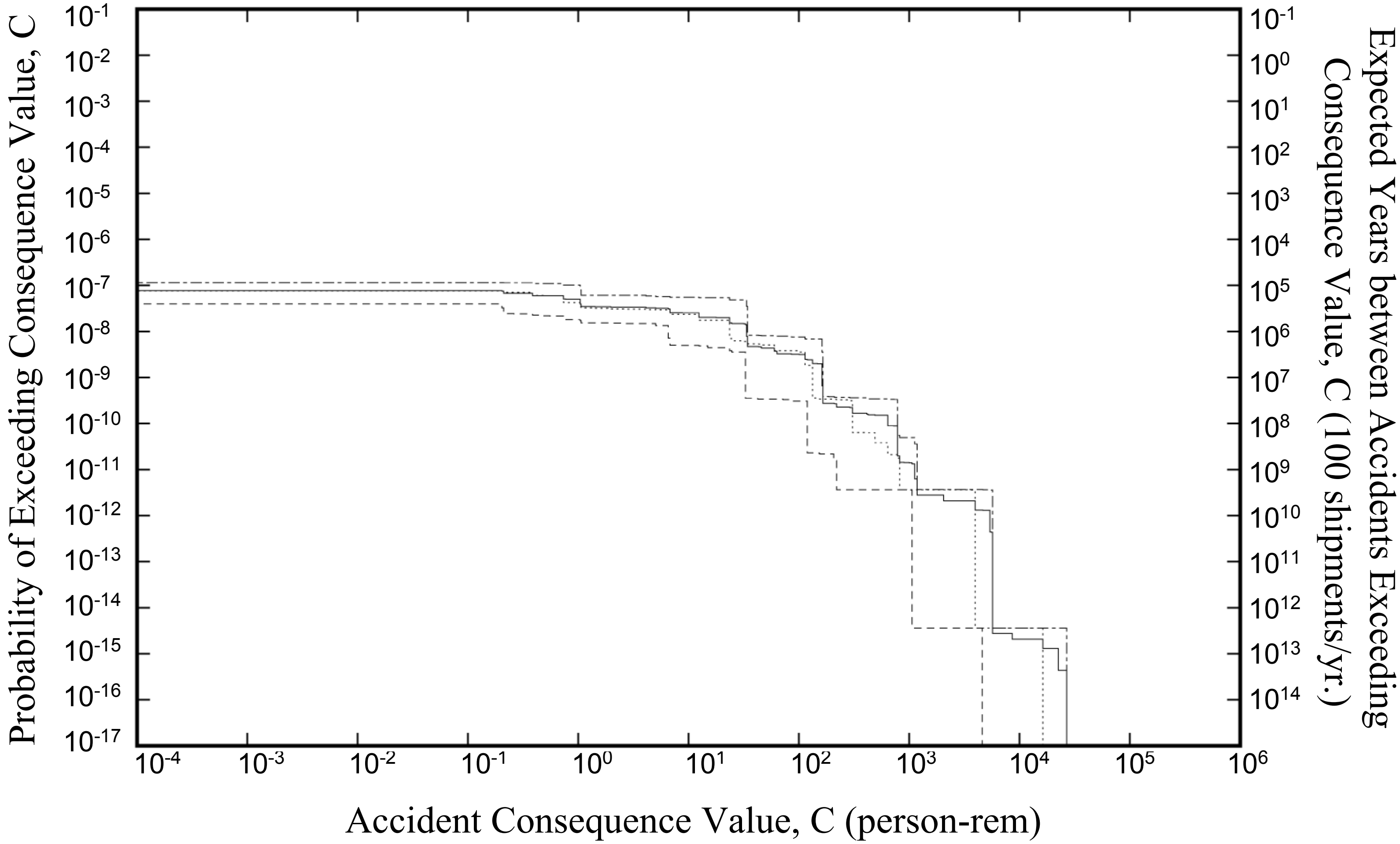

Figure 8.13 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the Maine Yankee to Skull Valley illustrative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

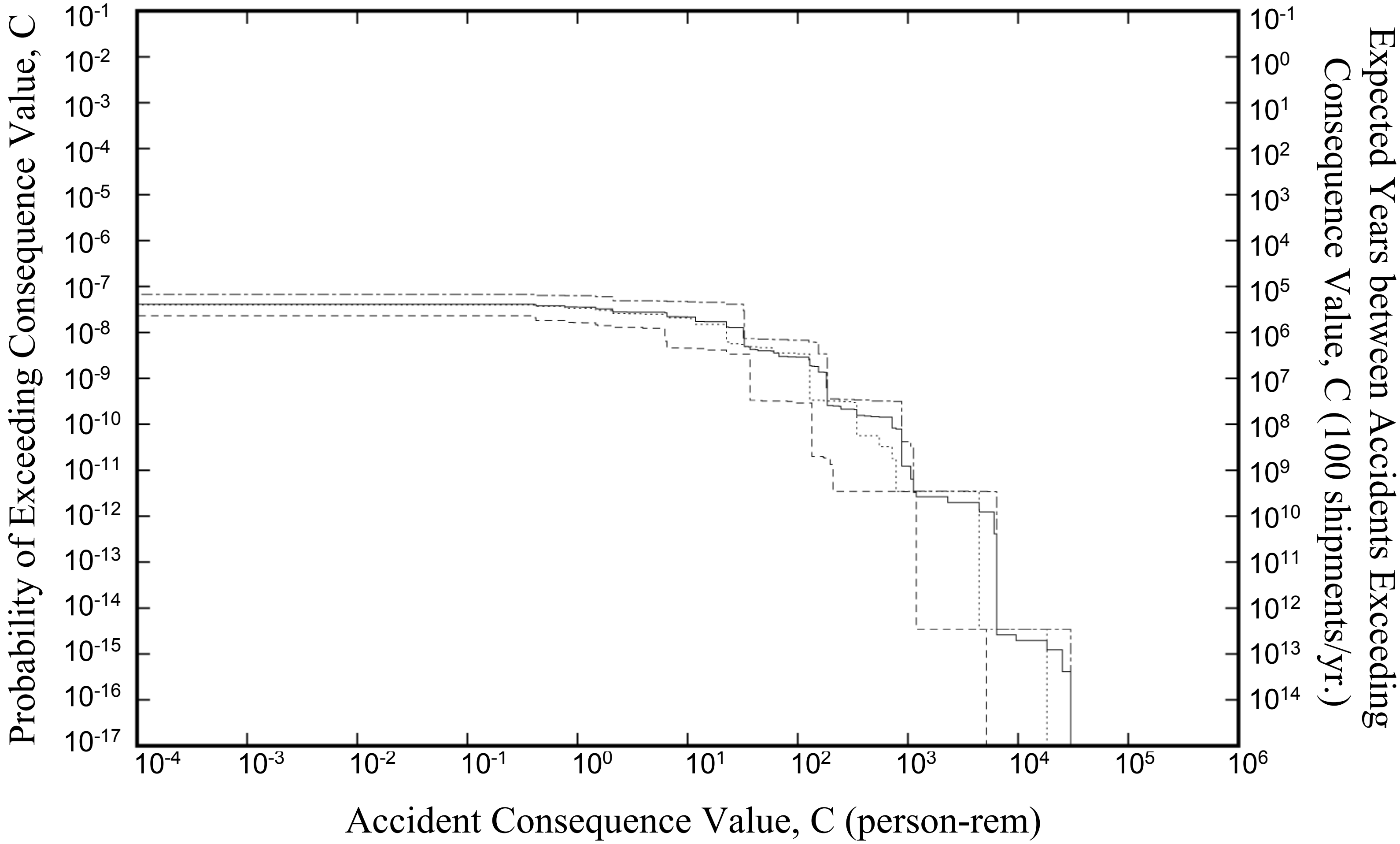

Figure 8.14 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the Maine Yankee to Savannah River Site illustrative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

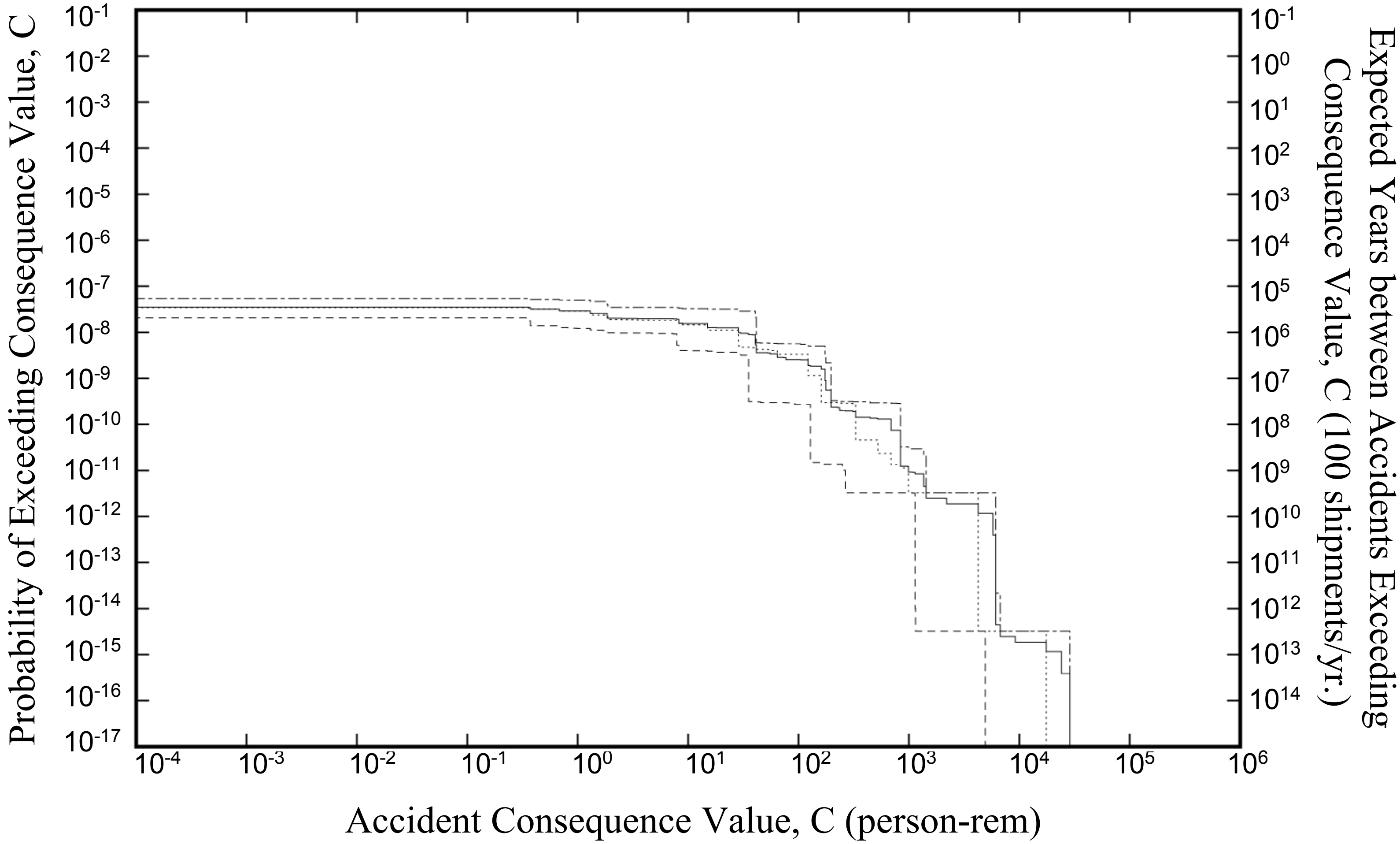

Figure 8.15 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the Kewaunee to Savannah River Site illustrative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

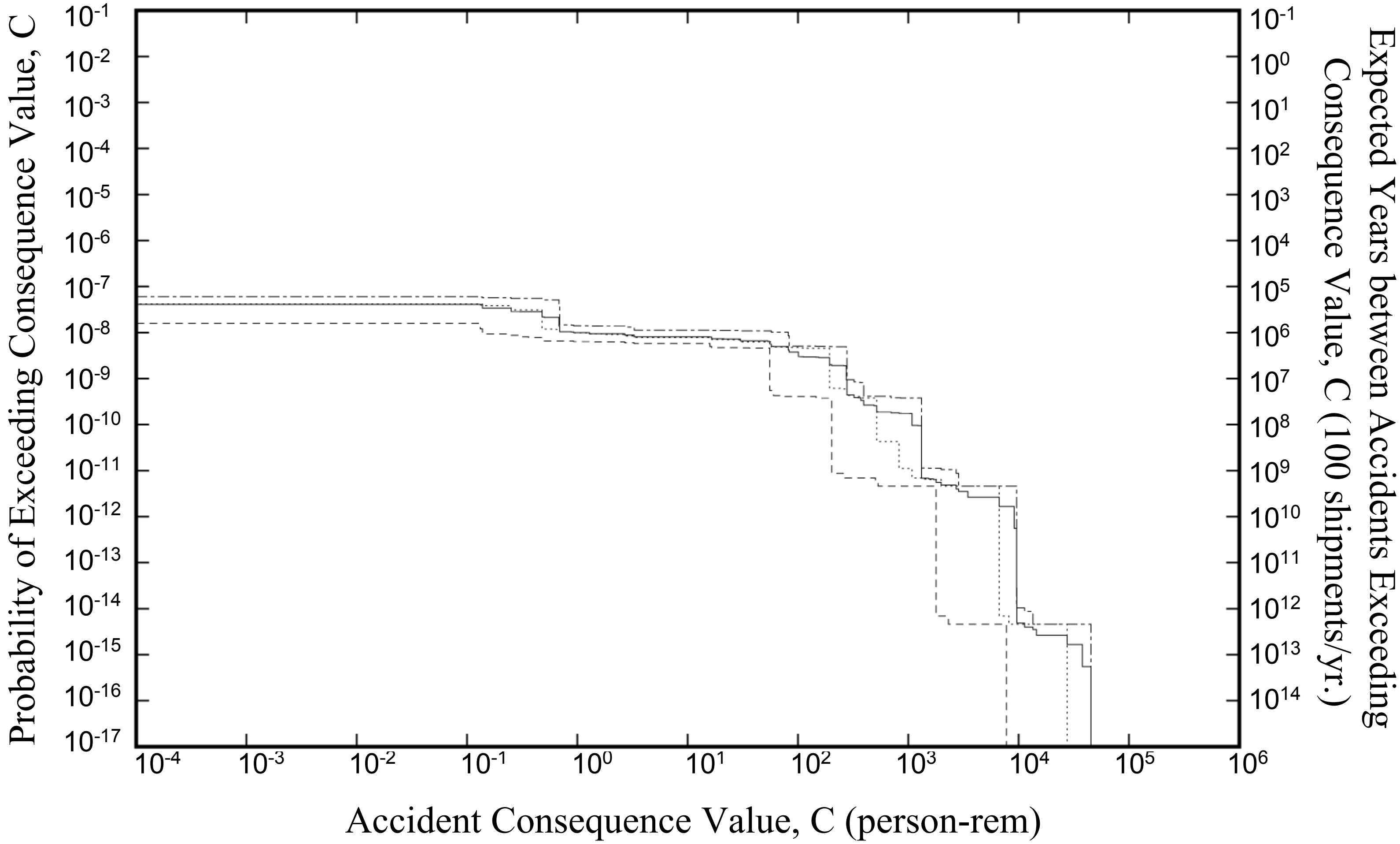

Figure 8.16 Truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel truck cask over the NUREG-0170 representative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

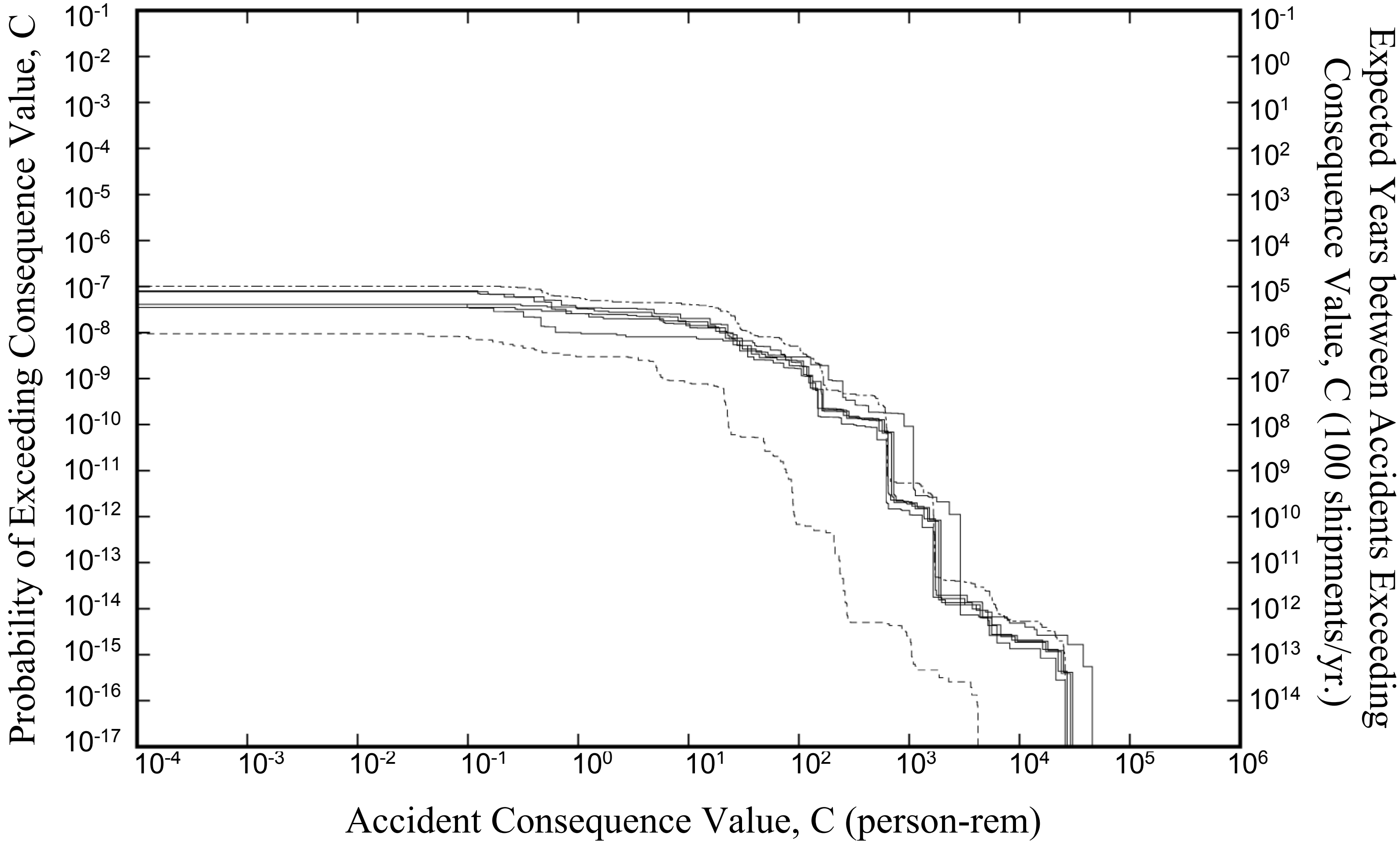

Figure 8.17 Comparison of truck accident population dose risk CCDFs for transport of PWR spent fuel in the generic steel-lead-steel cask over four illustrative truck routes and the NUREG-0170 representative truck route. Each underlying RADTRAN 5 calculation generated results for all of the 19 representative truck accident source terms.

Five Mean CCDFs (———), and Highest 95th (-·-·-·-·-) and Lowest 5th (---------) quantiles

Table 8.8 Incident-Free Population Dose Risks for Truck Transport of PWR Spent Fuel in a Generic Steel-Lead-Steel Truck Cask over Illustrative Routes

Metric	Population Dose Risks (person-rem)					
	Incident-Free					Accident
	Stops[a]		Other[b]	Total		
	Sleep[c]	No Sleep[d,e]		Sleep[c]	No Sleep[d]	
Crystal River Nuclear Plant to Hanford Site						
Mean =	1.470	0.0525	0.0581	1.530	0.111	9.53E-07
Standard Deviation =	0.722	0.0258	0.0281	0.722	0.038	5.92E-07
Maine Yankee Nuclear Plant to Skull Valley						
Mean =	1.300	0.0464	0.0524	1.350	0.099	1.29E-06
Standard Deviation =	0.637	0.0228	0.0252	0.637	0.034	7.81E-07
Maine Yankee Nuclear Plant to Savannah River Site						
Mean =	0.585	0.0209	0.0252	0.610	0.046	1.14E-06
Standard Deviation =	0.288	0.0103	0.0122	0.288	0.016	6.73E-07
Kewaunee Nuclear Plant to Savannah River Site						
Mean =	0.541	0.0193	0.0231	0.564	0.042	1.01E-06
Standard Deviation =	0.257	0.0092	0.0112	0.257	0.011	5.93E-07
NUREG-0170 Truck Route						
Mean =	0.779	0.0321	0.0304	0.810	0.063	1.28E-06
Standard Deviation =	0.383	0.0137	0.0147	0.383	0.020	6.68E-07

a. Exposures at rest, food, and refueling stops.
b. Sum of on-link, off-link, and crew doses.
c. Sleep means that the truck makes a rest stop of 8 hours once every 24 hours so the crew can sleep.
d. No Sleep means that the truck doesn't make any rest stops to allow the crew to sleep.
e. The No Sleep stop dose is obtained by dividing the Sleep stop dose by 28.

thereafter lies near to or above the 95th percentile CCDF. Thus, Figure 8.17 shows that the four illustrative truck routes yield accident population dose risks that lie toward the top of the range of accident population dose risks obtained using the LHS sample that contained 200 representative truck routes and, for accident population dose risks that exceed 100 person-rem, below the CCDF obtained using the NUREG-0170 truck route. The NUREG-0170 truck route CCDF lies generally higher than the illustrative truck routes CCDFs because, as Table 8.7 shows, the NUREG-0170 truck route has suburban and urban population densities that are substantially larger than those that characterize the illustrative truck routes.

Finally, Table 8.8 presents the mean (expected) incident-free population doses calculated by RADTRAN 5 for transport of PWR spent fuel in the generic steel-lead-steel cask along the illustrative routes. Table 8.8 shows that, as was true for the LHS calculations that examined truck transport of spent fuel using the representative set of 200 truck routes for specific real truck routes, total incident-free population dose risks again exceed accident population dose risks by factors of at least $3x10^4 = 0.042/1.29x10^{-6}$, if no sleep stops are made, to as much as

$2 \times 10^6 = 1.530/9.53 \times 10^{-7}$, if sleep stops are made; and that population doses incurred when the truck stops, for example to refuel, are quite similar, when no sleep stops are taken, and exceed all other incident-free population doses (e.g., on-link and off-link doses) by factors of about 25, if sleep stops are taken. Comparison of the results in Table 8.8 to those in Table 8.4 shows that all of the incident-free doses for illustrative truck routes, both those calculated with sleep stops and those calculated without sleep stops, fall within the range (defined by the maximum and minimum values calculated) of results obtained for incident-free doses using the LHS sample that contains 200 representative truck routes.

8.10.2 Monolithic Steel Rail Cask Results for Illustrative Routes

Figures 8.18 through 8.23 present the accident population dose risks and Table 8.9 presents the incident-free population dose risks for the RADTRAN 5 calculations that examined spent fuel transport in the generic monolithic steel rail cask over the four illustrative rail routes and the NUREG-0170 rail route. Figures 8.18 through 8.21 present the results obtained for the four illustrative real rail routes, and Figure 8.22 presents the results obtained for the NUREG-0170 rail route. Each of these figures presents CCDFs of the expected, 95th, median, and 5th percentile values of accident population doses that were calculated for the generic monolithic Steel rail cask carrying spent PWR high-burnup fuel along the indicated illustrative real rail route or for the NUREG-0170 representative rail route. In Figure 8.23, the mean (expected) CCDFs from each of these calculations are plotted and compared to the 5th and 95th percentile CCDFs depicted in Figure 8.11. Thus, Figure 8.23 compares the expected accident population dose results of the illustrative rail and NUREG-0170 rail route calculations to the range of the accident population doses results developed using the 200 representative rail routes that were constructed by LHS sampling from rail route parameter distributions. Figure 8.23 shows that (a) the CCDFs for the four illustrative rail routes are quite similar, (b) they all lie below the CCDF of 95th percentile values for the LHS calculation that examined the 200 representative rail routes, and (c) the CCDF for the NUREG-0170 rail route calculation lies below the illustrative route CCDFs until accident population doses exceed 1000 person-rem and then lies among them until the highest accident population doses are reached, whereupon it crosses all of the illustrative route CCDFs and even crosses the 95th percentile CCDF. Thus, Figure 8.23 shows that the four illustrative rail routes yield accident population doses that lie toward the top of the range of accident population doses obtained using the LHS sample that contained 200 representative rail routes and at all but the very highest population doses above the CCDF of mean population doses obtained using the NUREG-0170 rail route. The NUREG-0170 rail route lies generally lower than the illustrative rail route CCDFs because it is only half as long and because its suburban route fraction is 4 to 6 times smaller than those of the illustrative rail routes.

Finally, Table 8.9 presents the mean (expected) incident-free population doses calculated by RADTRAN 5 for transport of PWR high-burnup spent fuel in the monolithic steel rail cask along the illustrative rail routes. Table 8.9 shows that, as was true for the LHS calculations that examined truck transport of spent fuel using the representative set of 200 rail routes for specific real rail routes, incident-free population dose risks exceed accident population dose risks by factors of about 10^4, and other incident-free population doses (e.g., on- link and off-link doses) are larger than the population doses incurred when the train stops, for example in a classification yard, by factors of 2 to 3. Comparison of the results in Table 8.9 to those in Table 8.5 shows that

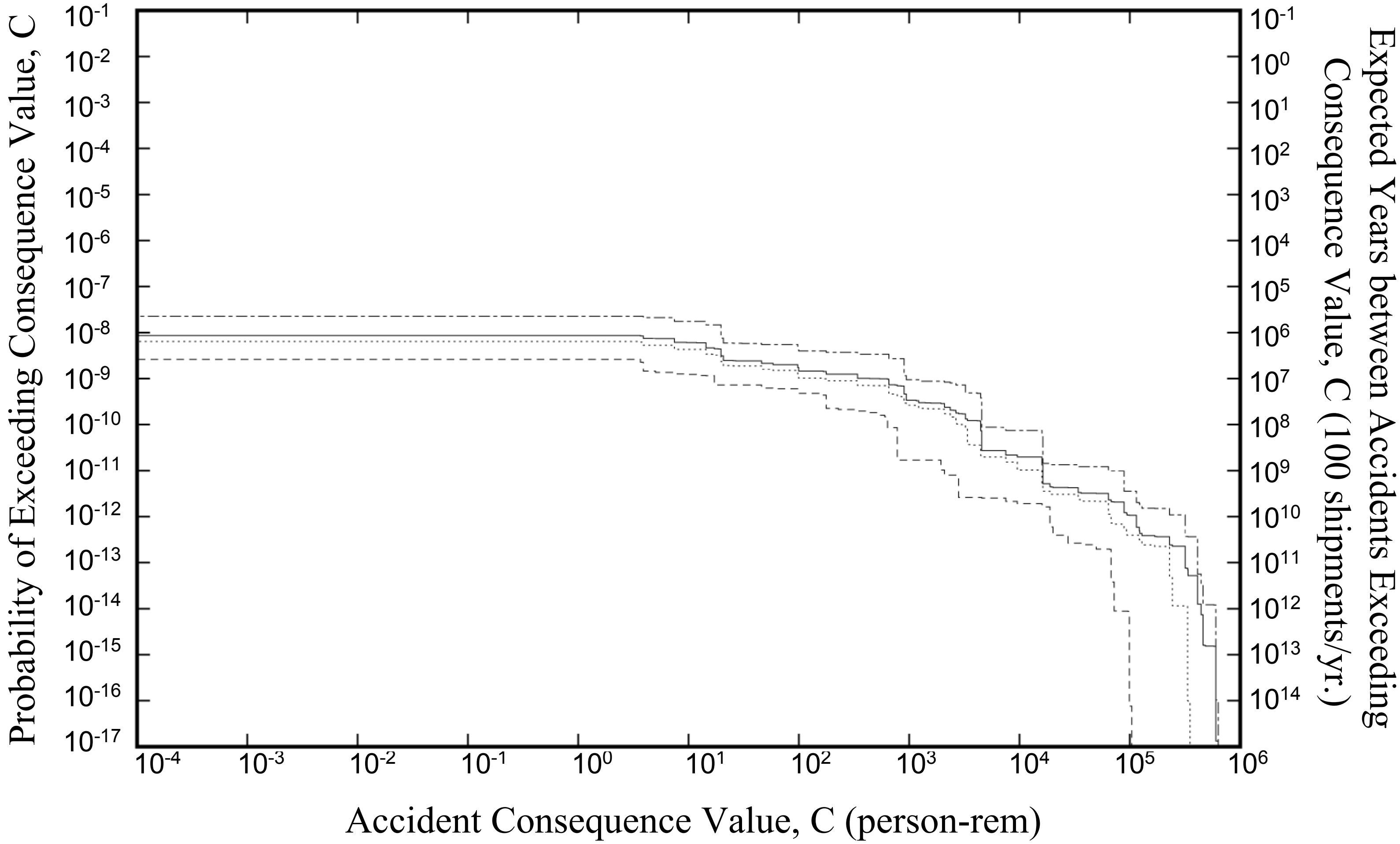

Figure 8.18 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the Crystal River to Hanford illustrative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

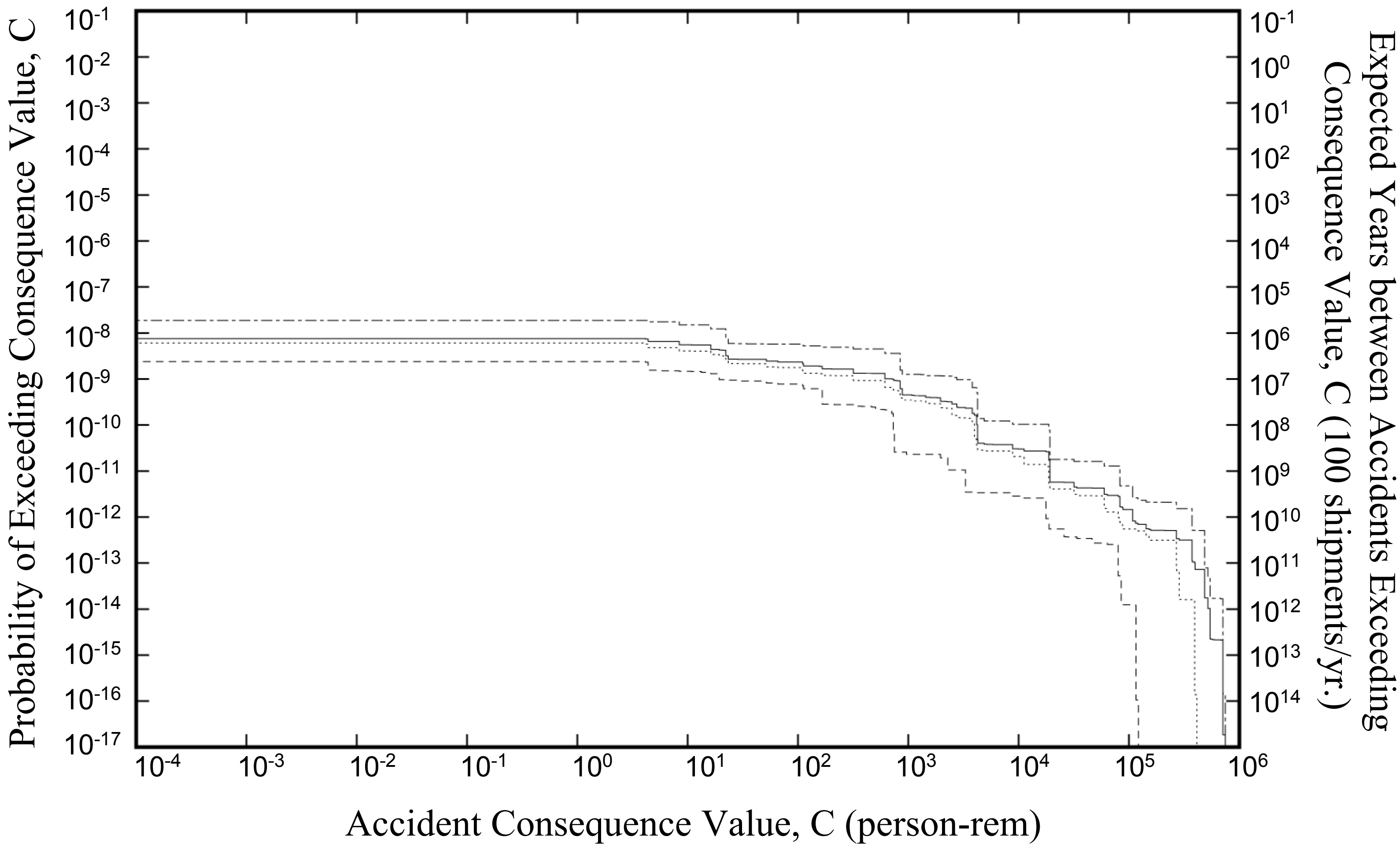

Figure 8.19 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the Maine Yankee to Skull Valley illustrative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

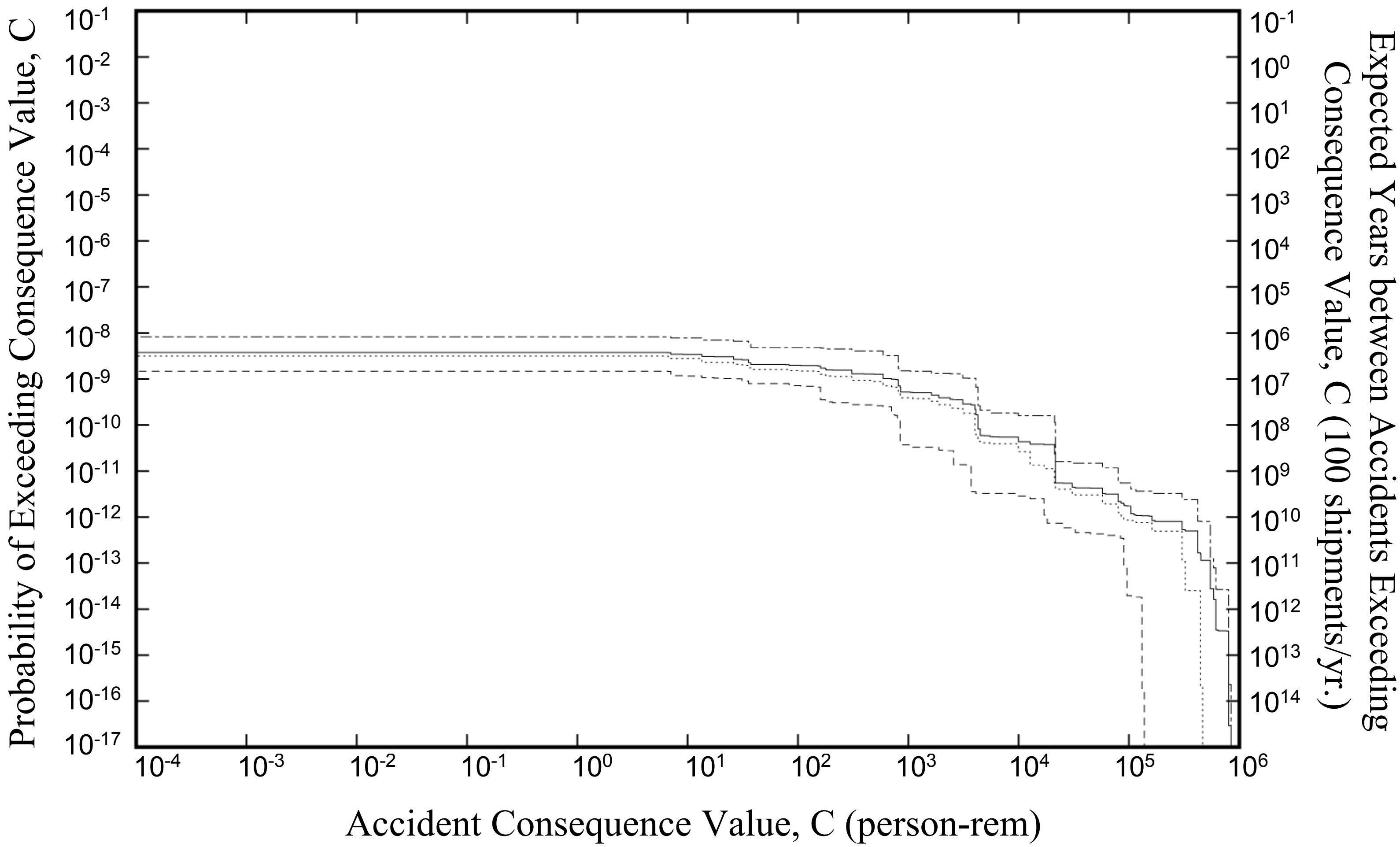

Figure 8.20 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the Maine Yankee to Savannah River Site illustrative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

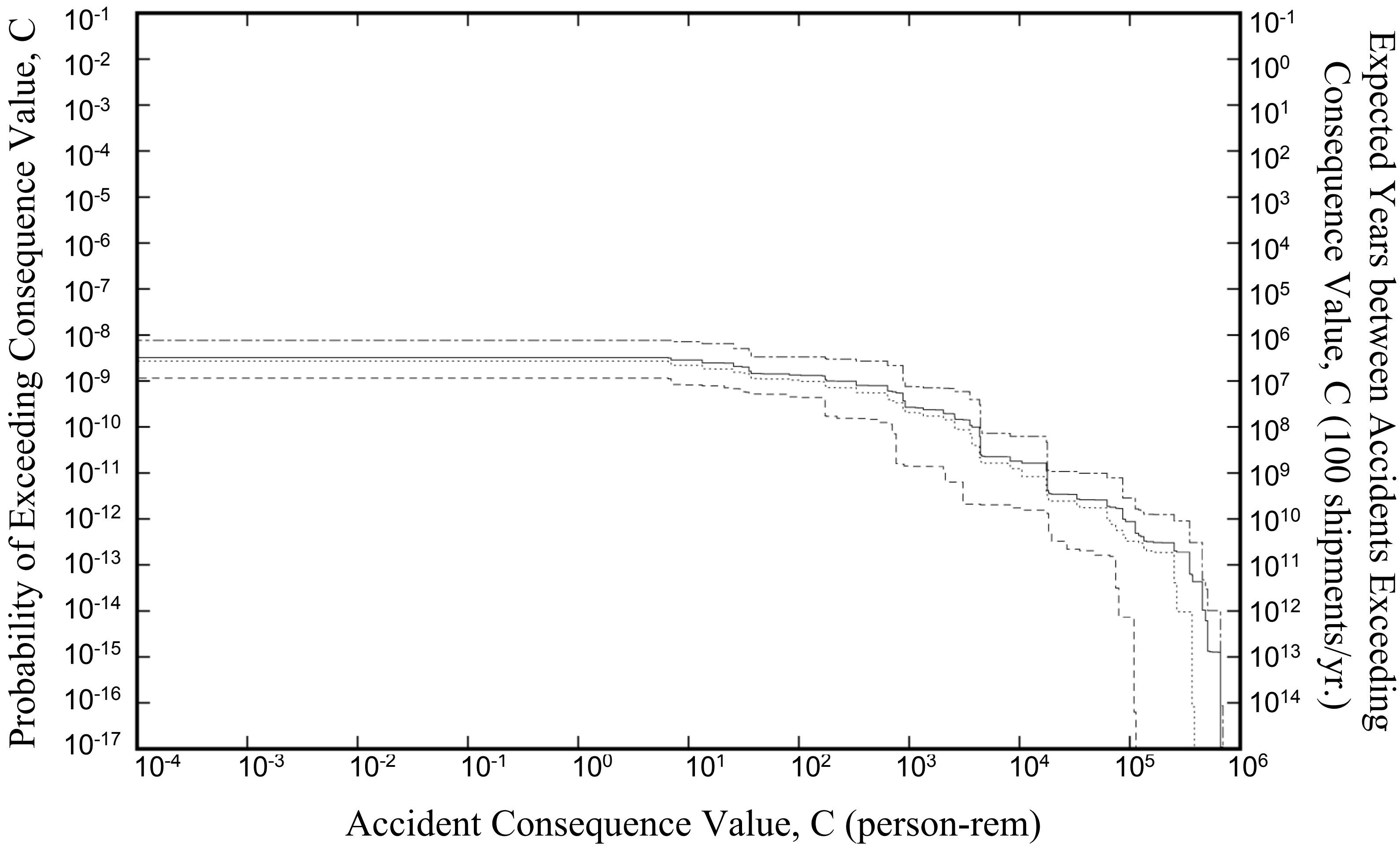

Figure 8.21 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the Kewaunee to Savannah River Site illustrative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

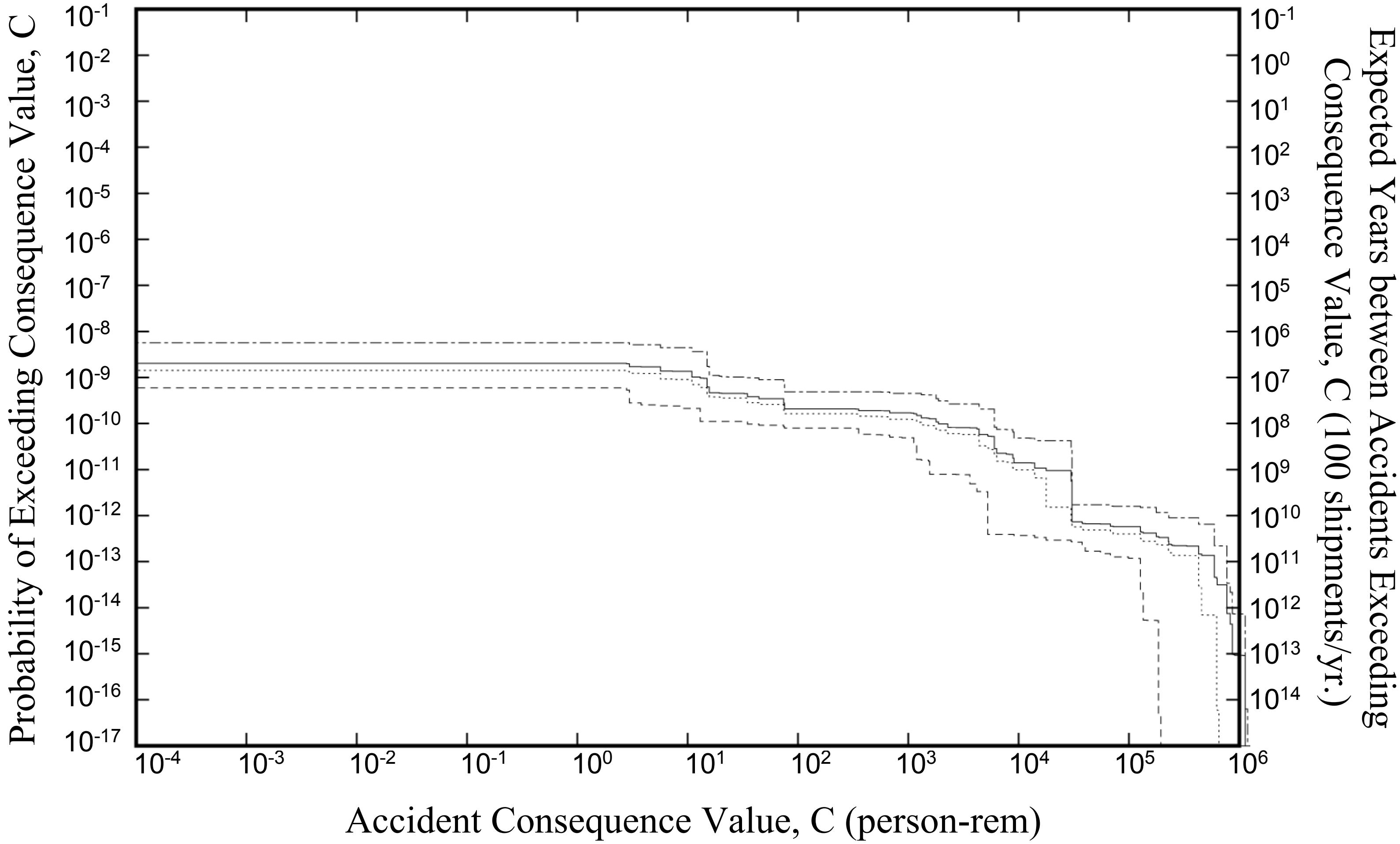

Figure 8.22 Rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel rail cask over the NUREG-0170 representative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Mean (———) CCDF, and 95th (-·-·-·-·-), 50th (··········), and 5th (---------) quantiles

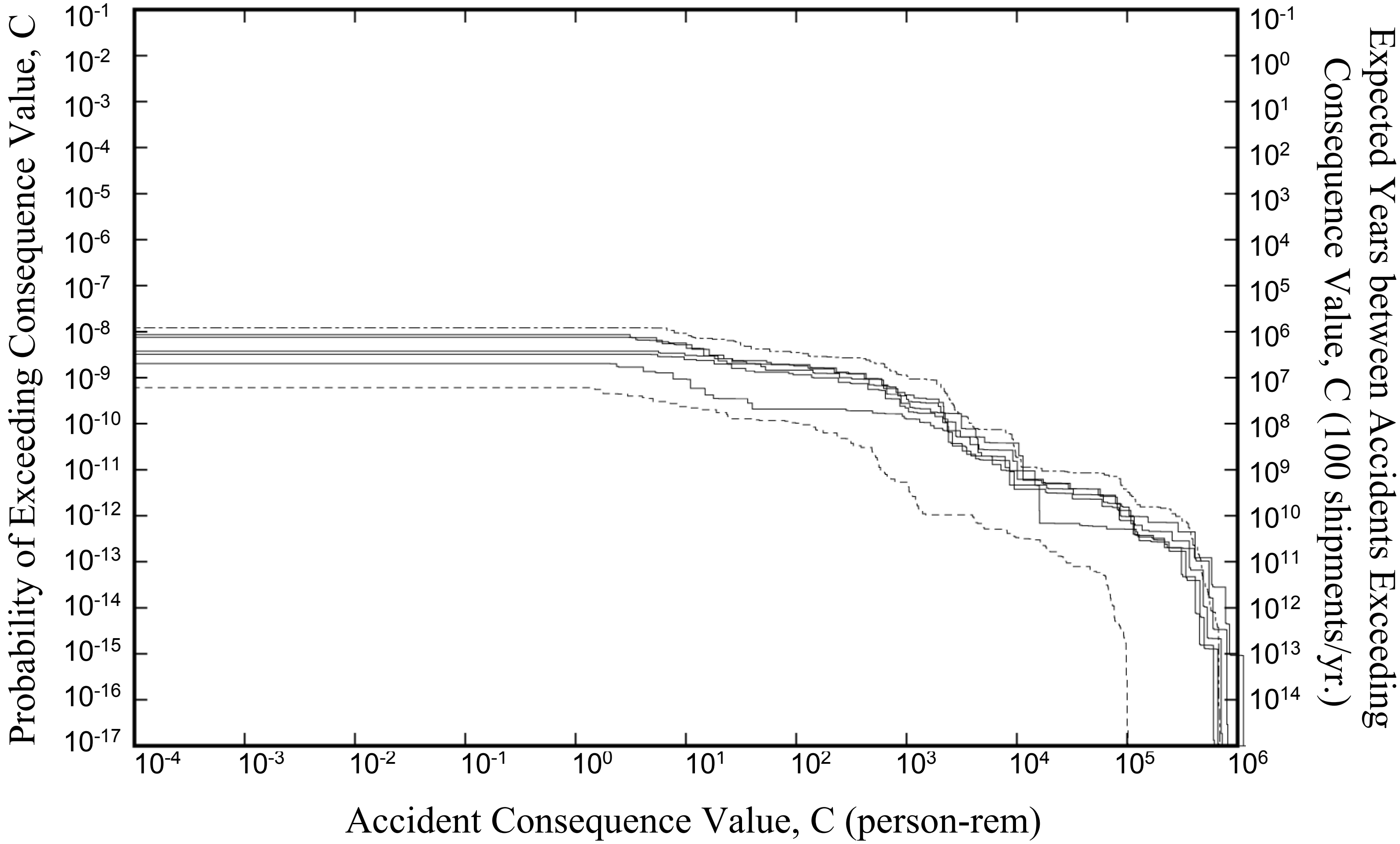

Figure 8.23 Comparison of rail accident population dose risk CCDFs for transport of PWR spent fuel in the generic monolithic steel cask over four illustrative rail routes and the NUREG-0170 representative rail route. Each underlying RADTRAN 5 calculation generated results for all of the 21 representative rail accident source terms.

Five Mean CCDFs (———), and Highest 95th (-·-·-·-·-·-) and Lowest 5th (··········) quantiles

Table 8.9 Incident-Free Population Dose Risks for Rail Transport of PWR Spent Fuel in a Generic Monolithic Steel Rail Cask over Illustrative Routes

Metric	Population Dose Risks (person-rem)			
	Incident-Free			Accident
	Stops[a]	Other[b]	Total	
Crystal River Nuclear Plant to Hanford Site				
Mean =	9.70E-03	2.89E-02	3.86E-02	2.44E-06
Standard Deviation =	5.71E-03	1.71E-02	1.80E-02	2.08E-06
Maine Yankee Nuclear Plant to Skull Valley				
Mean =	1.19E-02	2.75E-02	3.69E-02	3.25E-06
Standard Deviation =	7.00E-03	1.62E-02	1.77E-02	2.77E-06
Maine Yankee Nuclear Plant to Savannah River Site				
Mean =	1.02E-02	1.66E-02	2.70E-02	3.79E-06
Standard Deviation =	6.05E-03	9.84E-03	1.15E-02	3.27E-06
Kewaunee Nuclear Plant to Savannah River Site				
Mean =	7.61E-03	1.33E-02	2.09E-02	1.95E-06
Standard Deviation =	4.50E-03	7.87E-03	9.06E-03	1.68E-06
NUREG-0170 Rail Route				
Mean =	2.05E-03	6.46E-03	8.51E-03	1.11E-06
Standard Deviation =	1.21E-03	3.82E-03	4.01E-03	1.03E-06

a. Exposures at rest and refueling stops.
b. Sum of on-link, off-link, and crew doses.

the mean incident-free dose risks for illustrative rail routes fall largely within the range (defined by the maximum and minimum values calculated) of results obtained for mean incident-free dose risks using the LHS sample that contains 200 representative rail routes.

8.10.3 Rod Strain Failure Criterion Sensitivity Calculation

Because of radiation-induced hardening and hydride formation, the impact strains that cause spent fuel rods to fail during collision accidents decrease significantly as fuel burnup increases. In Section 5.4.1, a 4 percent average strain failure criterion for rod failure due to impact was developed by constructing a weighted summation of strain failure criteria by fuel burnup ranges using the fractional amounts of fuel in each burnup range as the weighting factors. The weighted summation assumed that high burnup spent fuel rods fail when subjected to 1 percent strains and that high average burnup fuel fails when subjected to 4 percent strains. The rod failure fractions presented in Table 7.18 were then developed by comparing the rod strains developed in Section 5.4.2 to this 4 percent strain criterion.

In order to examine the effect of the rod strain failure criterion on accident risks, one of the illustrative route calculations, the Crystal River to Hanford rail calculation that assumed spent fuel transport in a monolithic steel rail cask, was repeated assuming that all of the rods in the cask would fail during any collision accident, rather than some failing during collision accidents with speeds between 30 and 60 mph, more failing at speeds between 60 and 90 mph, and all failing when accident speeds exceed 90 mph. Because high burnup fuel rods will fail whever subjected to strains greater than 1 percent, besides examining the sensitivity of the accident risk analyses to rod failure strain criterion, this calculation also develops a result for high burnup fuel rods which are expected to fail during all collisions that exceed regulatory conditions (a 30 mph impact onto an unyielding surface).

Table 8.9 shows that, when a 4 percent average rod strain failure criterion was assumed, the mean accident risk for the Crystal River to Hanford rail route for a monolithic steel rail cask was calculated to be 2.44E-6 person-rem. When this calculation was repeated assuming rod failure fractions of 1.0 for all accident speed ranges, the calculated mean accident risk was found to be 4.69E-6 person-rem. Thus, even if all of the rods in a spent fuel cask were assumed to fail during any collision accident with a speed greater than 30 mph, accident risk estimates would increase by only a factor of two.

Accident risks increase by only a factor of two for two reasons. First, as the tables in Appendix D show, 10 of the 20 rail accident cases that lead to radioactive releases already have rod failure fractions for collision accidents that have values of 1.0, and 2 of the 10 that have failure fractions for collisions that are less than 1.0 lead to fires that fail all remaining unfailed rods. Second, although failing more rods increases the release of particulates (fuel fines), it decreases the release of Cs vapors because, once generated by heating by a fire, these vapors can now escape from failed rods only by diffusion, which is a very inefficient transport process. Thus, failing all of the rods on impact decreases the total release of Cs (Cs release in particulates increases but not enough to compensate for the virtual elimination of Cs release in vapors). Therefore, accident source terms increase much less than might be expected given the strong dependence of rod failure on rod strain levels. Finally, the fact that accident risks are increased by only a factor of two, when rod failure fractions are set to 1.0, shows that the approximate nature of the analysis used in Section 5.4.1 to develop the 4 percent average rod failure strain criterion was entirely justified.

8.11 Rail Routes with Heavy-Haul Segments and Intermodal Transfers

Transport of spent fuel by rail in a rail cask will require special heavy-haul truck transport over short route segments when either the nuclear power plant (e.g., the Maine Yankee and Kewaunee nuclear plants) or the storage site (e.g., the proposed Skull Valley interim storage site) are not serviced directly by a rail spur. Because the need for heavy-haul truck transport to or from rail route termini was neglected in all of the rail route calculations described in Sections 8.7 and 8.10.2, the magnitude of the incident-free dose risks (including handler dose risks incurred during intermodal transfers) and accident population dose risks that might result during heavy-haul truck transport to or from railheads was investigated for three real heavy-haul route segments:

1. the Maine Yankee nuclear plant to the railhead at Pejepscot Mills, Maine;
2. the Kewaunee nuclear plant to the railhead at Kewaunee, Wisconsin; and
3. the railhead at Timpie, Utah, to the proposed Skull Valley, Utah, interim storage site.

This section describes these calculations and compares the population dose risks calculated for these heavy haul segments to the population dose risks calculated for the specific real rail route that each heavy-haul segment would service.

For each heavy-haul route segment, route parameters for three aggregate segment links (urban, suburban, and rural link distances; population densities; and accident rates) were developed. Segment lengths and population densities were calculated for the non-interstate road segments from 1990 census data using the ArcView GIS software system. Rural and suburban accident rates were set to the means of the accident rate distributions developed in Section 3.4.2.3, and the value used for the urban accident rate was the value used in the LHS truck route calculations. Table 8.10 presents these route parameter values.

Table 8.10 Route Parameters for Heavy-haul Truck Transport Segments

Aggregate Link	Length (km)	Population Density (persons per km^2)	Accident Rate (accidents per km)
Maine Yankee Nuclear Plant to the Railhead at Pejepscot Mills			
Rural	15	31.6	2.2E-7
Suburban	21	318	4.1E-7
Urban	4.0	2570	5.2E-7
Kewaunee Nuclear Plant to the Railhead at Kewaunee			
Rural	17	38.5	2.2E-7
Suburban	1.0	90.8	4.1E-7
Urban	0.0	NA	NA
Railhead at Timpie to the Proposed Skull Valley Interim Storage Site			
Rural	46	0.21	2.2E-7
Suburban	0.0	NA	NA
Urban	0.0	NA	NA

Next, the set of PWR truck accident severity fractions and release fractions in Table 7.31 was modified by eliminating accidents (setting severity fractions to zero) that can not occur given the characteristics of heavy-haul transport (movement under escort at low speeds). Specifically, severity fractions were set to zero for all of the accident categories that describe accidents that occur with speeds greater than 60 mph (Accident Categories 1, 5 through 13, and 15 through 17). In addition, because the formation of a robust puncture probe during very-low-speed accidents is extremely improbable, the severity fraction for Accident Category 14 was also set to zero. Thus, rail cask failure during heavy-haul transport was assumed to be possible only for the three low-speed collision accident categories (Categories 2 through 4) that initiate fires and also for the fire-only accident category (Category 18). Then, because heavy-haul transport speeds are almost always < 30 mph (the calculation assumed 25 mph), the severity fractions for the remaining four accident categories were each decreased by a factor of ten. Finally, given this input data, RADTRAN 5 was used to calculate the population dose risks associated with heavy-haul truck transport over each of the three heavy-haul routes defined in Table 8.10. The results of these calculations are presented in Table 8.11.

Table 8.11 shows that, for these three heavy-haul route segments, other incident-free dose risks are about 10^3 to 10^6 times larger than the incident-free stop doses, and about 10^4 to 10^7 times larger than the accident dose risks. Comparison of these dose risks to the same dose risks listed in Tables 8.5 and 8.9 for transport over rail routes indicates that incident-free and accident dose risks for heavy haul transport to or from railheads will be negligible when compared to the population dose risks associated with transport over the rail portion of any route that requires both transport by heavy-haul truck and by train. Finally, comparison of the intermodal transfer handler population dose risks in this table to the total incident-free dose risks presented in Tables 8.5 and 8.9 shows that adding intermodal transfers to any rail route will significantly increase total population dose risks because the handlers must work close to the cask for significant periods of time while attaching lifting hardware, inspecting the cask, and performing other transfer operations.

Table 8.11 Heavy-Haul Incident-Free and Accident Population Dose Risks

	Population Dose Risks (person-rem)				
	Incident-Free				
Metric	**Stops[a,b]**	**Other[c]**	**Total**	**Accident**	**Handling[d]**
Maine Yankee Nuclear Plant to the Railhead at Pejepscot Mills					
Mean =	3.8E-07	5.1E-04	5.1E-04	8.0E-08	1.4E-02
Standard Deviation =	2.2E-07	3.0E-04	3.0E-04	4.4E-08	8.5E-03
Kewaunee Nuclear Plant to the Railhead at Kewaunee					
Mean =	2.1E-07	1.7E-04	1.7E-04	2.2E-09	1.4E-02
Standard Deviation =	1.2E-07	1.1E-04	1.1E-04	1.4E-09	8.5E-03
Railhead at Timpie to the Proposed Skull Valley Interim Storage Site					
Mean =	4.5E-10	4.2E-04	4.2E-04	2.6E-11	1.4E-02
Standard Deviation =	2.6E-10	2.7E-04	2.7E-04	1.8E-11	8.5E-03

a. Intermodal transfer stop dose to members of the public.
b. Short segment lengths mean no stops are made for inspections or to refuel, eat, or sleep.
c. Sum of on-link, off-link, and crew doses.
d. Intermodal transfer dose risk to cask handlers.

8.12 Loss of Shielding Accidents

The loss of shielding (LOS) accident model uses the entire radionuclide content of the material to determine source strength because it was built for less robust (Type A) packages (e.g., radiopharmaceutical shipments) that could lose all or part of their shielding in serious accidents. With spent-fuel casks, however, loss of shielding is expected to be localized to a small fraction of the total surface area of the cask.

Although the STOP subroutine is generally used to evaluate incident-free doses at stops, it is also suited to spent fuel cask LOS scenarios because the subroutine requires only dose rate, source dimension, and exposure duration as input values. These are used to construct a point source of the appropriate source strength to estimate radiation exposure fields, as is used for the RADTRAN incident-free exposure model. Population may be modeled as being uniformly distributed around the source in one or more annular areas with user-defined radii and population densities. Exposure duration is taken to be the time that passes before emergency responders establish an exclusion area around the accident site. In the absence of specific information for this variable, 25 minutes in urban areas and 40 minutes in rural and suburban areas were the values used.

To use the RADTRAN STOP model to assess LOS consequences for accidents involving casks, three factors must be calculated for each accident severity category:

- Severity fraction for each LOS accident case.
- Dose rate (dose rate at 1 m from surface of cask after the LOS accident has occurred).
- Maximum dimension and geometry of the unshielded area.

8.12.1 Severity Fractions, Dose Rates, and Cask LOS Areas

Severity fractions for ten LOS accident cases are developed by combining the train accident cases presented in Table 7.11 into 6 groups as follows: Cases 4, 5, and 6 which have accident speeds from 30 to 60 mph, Cases 1, 7, 8, and 9 which have accident speeds from 60 to 90 mph, Cases 2, 10, 11, 12, and 13 which have accident speeds from 90 to 120 mph, Cases 3, 13, 14, 15, and 16 which have speeds > 120 mph, Case 20 which is all fire only accidents that produce lead slump by melting, and Cases 16, 17, 18, and 19 which are collision accidents during which the cask shell is punctured, which also lead to large fires and thus to the loss of melted lead out the shell puncture. Severity fractions for these ten LOS accident cases are developed by summing the severity fractions for the accident cases which contribute to each LOS case and multiplying by the chance that the accident is an end or a corner impact (the finite element calculations do not show LOS for side impact accidents).

The maximum exposed length of a spent-fuel assembly (at least for end drops where lead slumps and separates from one end of the cask) is determined from the finite element analyses of cask shielding damage for each scenario. This exposed length is then expressed as a fraction of the length of a full PWR assembly (200 inches).

The LOS fraction is then used to calculate a Source-Strength Multiplier, which is the number by which the maximum dose rate at 1 m from an unshielded fuel assembly must be multiplied to yield the maximum dose rate 1 m from the cask on the centerline of the field of view of the shielding damage. Because lead slump often occurs at the ends of the cask where the fittings are and where the lowest burnup fuel is located, neglect of this consideration increases the conservatism of the source strength estimates.

To calculate the Source-Strength Multiplier of a steel-lead-steel train cask, the following approach was used. As is shown in Figure, 8-24, the dose rate at 1 m in the center of the zone of shielding damage was modeled as the integrated sum of dose rate contributions from the fuel surface extending in an arc from 0 degrees to approximately 60 degrees multiplied by 2 to account for symmetry. The fuel surface was modeled as being a section of a cylinder with a diameter equal to 1.65 m (the same as the cask ID) and a width equal to the maximum exposed length.

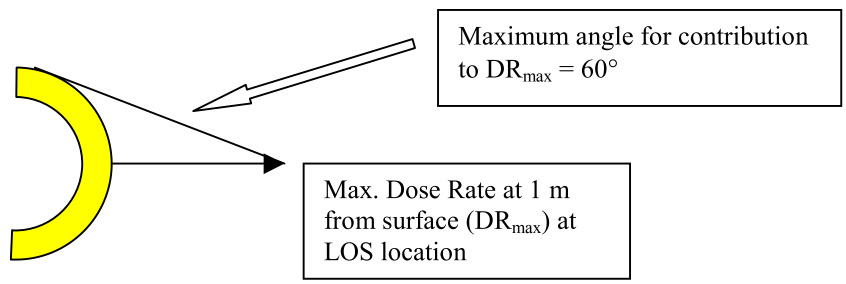

Figure 8.24 Representation of spent fuel surface for dose rate calculation for LOS scenarios.

Table 8.12 presents the severity fractions, LOS fractions, and source strength multipliers used in the LOS accident calculations. The following comments qualify the development of the values of these parameters:

1. For LOS Cases 1 through 8, impact forces are modeled as causing lead slump, and the maximum length of exposed fuel for each of these cases was taken from the appropriate finite element analysis.

2. For LOS Cases 9 and 10, the accident leads to a fire. Case 10 involves lead melt combined with puncture that allows some of the lead to flow out of the cavity between the inner and outer cask shells. Because the location of the puncture with respect to the ground surface cannot be predicted, on the average it is assumed to allow approximately one-half of the lead to flow out. Thus, a value of 0.5 for fractional exposure was assigned to this accident case.

3. In all cases, the approximately 3 inches of steel that comprise the inner and outer shell are modeled as remaining in place, and the shielding they continue to provide is accounted for in this model.

4. The Source-Strength Multiplier is calculated by expressing the result from the integration (Step 1) as a fraction of the dose rate from a single fully exposed assembly and multiplying by the total number of assemblies exposed.

5. This value is then entered as a modifier (shielding factor) into the RADTRAN STOP model, and the package dose rate is replaced by the dose rate for the fully exposed fuel. The product of these two variables yields dose rate in area of LOS.

Table 8.12 Values of Severity Fractions, LOS Fractions, and Source-Strength Multipliers for Ten LOS Accident Cases

LOS Case	Accident Type	Accident Conditions	Train Accident Cases	Sum Case Probabilities	Severity Fraction	LOS Fraction	Source-Strength Multiplier
1	Collision	end	4,5,6	3.049E-05	1.707E-06	0.052	0.215
2	Collision	end	1,7,8,9	8.273E-06	4.633E-07	0.158	0.637
3	Collision	end	2,10,11,12	5.730E-07	3.209E-08	0.264	1.017
4	Collision	end	3,13,14,15	4.524E-09	2.534E-10	0.368	1.336
5	Collision	corner	4,5,6	3.049E-05	2.201E-05	0.033	0.137
6	Collision	corner	1,7,8,9	8.273E-06	5.973E-06	0.096	0.394
7	Collision	corner	2,10,11,12	5.730E-07	4.137E-07	0.158	0.637
8	Collision	corner	3,13,14,15	4.524E-09	3.266E-09	0.255	0.986
9	Fire Only	T > 350°	20	4.905E-05	4.905E-05	0.029	0.120
10	Fire	T > 350°C & puncture	16,17,18,19	4.150E-10	1.660E-09	0.500	1.668
11	No LOS				9.999E-01	0.000	

8.12.2 Maximum Dimension of LOS Area

The maximum LOS area is obtained in a relatively conservative manner by using the product of LOS fraction and fuel assembly length as one dimension of a rectangle. The second dimension is set equal to the ID of the cask. The diagonal of this rectangle is entered into RADTRAN as the maximum characteristic dimension, which is used internally to calculate a shape factor (k_0) for a point source.

8.12.3 Final Calculation

The dose rate and dimension values entered as described above allow the user to calculate population dose for persons, who remain at specified distances from the LOS accident location for specified lengths of time, by treating the results of the LOS event as a point source. For real LOS accidents, cask orientation combined with shielding by the undamaged portions of the cask shell and also by nearby buildings would mean that radiation exposures would be limited in extent by the view factor to the spent fuel through the damaged portions of the cask shell that now provide no shielding. However, because the exact geometry of an accident cannot be predicted in advance, a point-source model and a uniformly distributed surrounding exposed population was used. Accordingly the estimates of the LOS accident dose risks should be somewhat conservative.

8.12.4 An Example of an LOS Calculation

As an example of an LOS risk estimate, a steel-lead-steel rail cask containing PWR fuel assemblies was considered. For an approximate surface dose rate of 50,000 rem/hr for five-year cooled spent fuel, the dose rate at 1 m from the surface of one face at mid-length of the assembly was calculated by modeling the assembly as a line source 5 m long. The resulting value, 3500 rem/hour, was then attenuated by 3 inches of steel using an approximate photon spectrum derived from the isotopic inventory for PWR spent fuel before subtracting insignificant isotopes relative to their A_2 values [8-7]. Since the source of the surface dose rate quoted above did not specify neutron and gamma fractions, the attenuation due to 3 inches of steel treats the radiation as 100% gamma; this yields a conservative result for radiation outside the cask. The radionuclides that account for 97 percent of the resulting dose rate are Co-60, Cs-134, Cs-137, and Eu-154, as may be expected from the their photon energies. The result, 20 rem/hr, representing the dose rate from a single PWR fuel assembly in a steel-lead-steel rail cask without the lead shielding, was then multiplied by the appropriate Source-Strength Multiplier in Table 8.12 to provide the required RADTRAN 5 input. The source dimension used in modeling the cask as a point source in RADTRAN 5 was taken to be the diagonal of the rectangular exposed area (viewed at right angles to the cask axis) for each case in Table 8.12. These two sets of parameters were used to define ten "VEHICLEs" in RADTRAN 5, one for each of the ten cases in Table 8.12.

The RADTRAN 5 stop model was used to define three LOS accident locations, i.e. rural, suburban, and urban. Population densities for these three stop definitions were assumed to equal the means of the respective population density distributions for each region (i.e., 10.1, 336, and 2195 persons per square kilometer, respectively). The area occupied by these populations was an annulus with a 10 m inner radius and an 800 m (1/2 mile) outer radius; the latter yields a dose rate well below 10 mrem/hour in each case. The standard shielding factors (1.0, 0.87 and 0.018) and emergency response times (0.67, 0.67, and 0.42) for rural, suburban, and urban areas, respectively, were applied to the three stop definitions. Table 8.13 presents route-portion lengths, mean rail accident rates, the severity fractions given in Table 8.13, the consequences calculated by RADTRAN 5, and the risks (probability times consequence) for each of the ten cases defined. The total LOS risk of 9.1E-11 person-rem may be compared with the PWR steel-lead-steel rail cask results given in Table 8.5 to see that this risk is much smaller than the dispersion accident value. In addition, the sum of the two risks (representing an accident in which there is loss of shielding and dispersion of cask contents) is well within the variability of the dispersion value alone.

8.13 Population Dose Risks for Shipment of the Entire 1994 Spent Fuel Inventory

The incident-free and accident population dose risks reported in the previous sections were calculated for single shipments of one Type B spent fuel cask by truck or by train. In this section, the results of those calculations are used to estimate the population dose risks that would be associated with the shipment of the entire 1994 inventory of commercial BWR and PWR spent fuel [8-2]. Table 8.14 presents the total numbers of BWR and PWR assemblies in the 1994 spent fuel inventory, the number of truck or rail shipments required to ship all of the BWR or all of the PWR assemblies in each of the four generic casks examined by this study, and the incident-free and accident population dose risks associated with the shipment of all of the BWR assemblies, all of the PWR assemblies, and their sums (i.e., the population dose risks for shipping the entire 1994 inventory). The population dose risks for transport by rail presented in this table do not include any doses to handlers that might be incurred during intermodal transfers (e.g., from heavy haul truck to rail car).

Table 8.13 Results of Loss of Shielding Risk Calculation

Case	Pop. Zone	Length (km)	Acc. Rate (per km)	Sev. Frac.	Probability	Consequence (dose, rem)	Dose Risk
1	Rural	1777	4.40E-08	1.71E-06	1.34E-10	0.0021	2.81E-13
	Suburban	541	4.40E-08	1.71E-06	4.07E-11	0.06	2.44E-12
	Urban	35	4.40E-08	1.71E-06	2.63E-12	0.0051	1.34E-14
2	Rural	1777	4.40E-08	4.63E-07	3.62E-11	0.0071	2.57E-13
	Suburban	541	4.40E-08	4.63E-07	1.10E-11	0.206	2.27E-12
	Urban	35	4.40E-08	4.63E-07	7.13E-13	0.0175	1.25E-14
3	Rural	1777	4.40E-08	3.21E-08	2.51E-12	0.0133	3.34E-14
	Suburban	541	4.40E-08	3.21E-08	7.64E-13	0.385	2.94E-13
	Urban	35	4.40E-08	3.21E-08	4.94E-14	0.0326	1.61E-15
4	Rural	1777	4.40E-08	2.53E-10	1.98E-14	0.0221	4.37E-16
	Suburban	541	4.40E-08	2.53E-10	6.02E-15	0.639	3.85E-15
	Urban	35	4.40E-08	2.53E-10	3.90E-16	0.0541	2.11E-17
5	Rural	1777	4.40E-08	2.20E-05	1.72E-09	0.0013	2.24E-12
	Suburban	541	4.40E-08	2.20E-05	5.24E-10	0.0373	1.95E-11
	Urban	35	4.40E-08	2.20E-05	3.39E-11	0.0032	1.08E-13
6	Rural	1777	4.40E-08	5.97E-06	4.67E-10	0.004	1.87E-12
	Suburban	541	4.40E-08	5.97E-06	1.42E-10	0.115	1.63E-11
	Urban	35	4.40E-08	5.97E-06	9.19E-12	0.0097	8.92E-14
7	Rural	1777	4.40E-08	4.14E-07	3.24E-11	0.0071	2.30E-13
	Suburban	541	4.40E-08	4.14E-07	9.85E-12	0.206	2.03E-12
	Urban	35	4.40E-08	4.14E-07	6.38E-13	0.0175	1.12E-14
8	Rural	1777	4.40E-08	3.27E-09	2.56E-13	0.013	3.32E-15
	Suburban	541	4.40E-08	3.27E-09	7.78E-14	0.377	2.93E-14
	Urban	35	4.40E-08	3.27E-09	5.04E-15	0.032	1.61E-16
9	Rural	1777	4.40E-08	4.91E-05	3.84E-09	0.0011	4.22E-12
	Suburban	541	4.40E-08	4.91E-05	1.17E-09	0.0331	3.86E-11
	Urban	35	4.40E-08	4.91E-05	7.55E-11	0.0028	2.12E-13
10	Rural	1777	4.40E-08	1.66E-09	1.30E-13	0.035	4.54E-15
	Suburban	541	4.40E-08	1.66E-09	3.95E-14	1.01	3.99E-14
	Urban	35	4.40E-08	1.66E-09	2.56E-15	0.0858	2.19E-16
Total							9.12E-11

Table 8.14 shows that, for shipment of the entire 1994 spent fuel inventory, accident dose risks are negligible when compared to incident-free dose risks, and that the magnitude of these risks changes significantly depending on the mode of shipment (truck or rail) and the type of cask

Table 8.14 Incident-Free and Accident Population Dose Risks for Shipment of the Entire 1994 Spent Fuel Inventory (person-rem)

Spent Fuel Type	Rail Shipments		Truck Shipments	
	Monolithic Steel Cask	Steel-Lead-Steel Cask	Steel-Lead-Steel Cask	Steel-DU-Steel Cask
	Assemblies in Total 1994 Inventory			
BWR	60144			
PWR	44598			
	Assemblies per Cask			
BWR	52	52	2	7
PWR	24	24	1	3
	Required Number of Shipments			
BWR	1157	1157	30072	8592
PWR	1858	1858	44598	14866
Total	**3015**	**3015**	**74670**	**23458**
	Incident-Free Stop Dose Risks[a,b,c]			
BWR	5.1	5.1	460	130
PWR	8.1	8.1	680	230
Total	**13.2**	**13.2**	**1140**	**360**
	Other Incident-Free Population Dose Risks[a,b]			
BWR	18.4	18.4	870	250
PWR	29.5	29.5	1280	430
Total	**47.9**	**47.9**	**2150**	**680**
	Total Incident-Free Population Dose Risks[a,b]			
BWR	24	24	1330	380
PWR	37	37	1960	660
Total	**61**	**61**	**3290**	**1040**
	Accident Population Dose Risks[a]			
BWR	0.0017	0.011	0.010	0.0093
PWR	0.0037	0.018	0.036	0.034
Total	**0.0054**	**0.028**	**0.046**	**0.043**

a. Values have been rounded to two significant figures.
b. Because the probability of occurrence of incident-free doses is 1.0, incident-free doses and incident-free dose risks have the same values.
c. Truck stop dose risks assume shipment without stops to sleep.

used for the shipments. The dependence of incident-free doses on shipment mode and cask type means that the incident-free doses for each year in the full spent fuel shipment campaign could vary significantly depending on the mix of assemblies shipped and the mode and cask used for each shipment made during a given year. For example, if the shipments take place over 20 years, the ratio of PWR to BWR assemblies shipped each year is the same as the ratio in the total inventory, all shipments are by rail in monolithic steel and/or steel-lead-steel rail casks, and handler doses during any intermodal transfers are neglected, then the total incident-free population dose per year would be about 1.3 person-rem. Conversely, if the shipments take place over 20 years, the ratio of PWR to BWR assemblies shipped each year is the same as the ratio in the total inventory, and all shipments are by truck in steel-lead-steel truck casks (the smaller capacity truck cask), then the total incident-free population dose per year would be about 130 person-rem, which is 100 times larger than the incident-free population dose for rail shipments.

8.14 Individual Dose Estimates

Besides the population dose estimates that are the basis of the CCDF's described above, RADTRAN estimates dose within areas downwind of the accident site. Individuals who might be within these areas at various distances from the accident site are counted as having received the dose predicted for that area. These doses are directly dependent on the magnitude of the source term for the specific representative accident being considered and assume that the individual remains outdoors directly in the path of the passing radioactive plume for the entire period of the accident/release event. Under these unlikely conditions and the very unlikely sequence of events that yield a source term at all, there is a potential for persons close to the accident location to receive a relatively large radiation dose. These accident conditions are associated with the population doses at the extreme right edge of the CCDF's in the preceding figures.

As an example of the doses that might be received from accidents involving spent fuel shipments, results from the RADTRAN calculations for rail shipment from Maine Yankee to Skull Valley, one of the illustrative routes discussed earlier, will examined in greater detail. For this discussion, a rail shipment was used because it presented the largest possible source term (because of the large number of spent fuel assemblies a rail cask contains). Generally speaking, the dose that could be received by a person decreases rapidly with distance from the point of release and the highest doses are received at the points closest to the accident. Similarly dose decreases with lateral distance from the maximum dose point (centerline) at any distance, i.e., as the distance from the center of a radioactive plume increases the inhalation/immersion dose decreases. As a result, the areas in which the highest doses could be received have a relatively small area. In addition, locations very close to the site of the accident are unlikely to be occupied by people for any length of time after an accident because of evacuation and crowd control measures by first responders. Thus, the shortest distance at which individuals might be expected to receive doses should be beyond 100 to 200 meters (330 to 660 feet) from the accident site.

In the distance range given, doses that could be received by individuals standing outdoors and directly under the passing radioactive plume for the entire time of passage range from 3 to 500 rem (50 yr CEDE) for the extremely unlikely collision/fire events (on the order of 1×10^{-10} per shipment) estimated to result in a significant release of material from a cask. The doses associated with these extremely unlikely events are relatively high but not so large that any early fatality is predicted (as is true for all RADTRAN calculations completed for this report) nor would an early fatality from radiation actually be expected to result. The largest of these doses, if received, could pose a significant, though not life threatening, health hazard to anyone so exposed, but there are many conservative factors in the RADTRAN calculations that come into play to make the likelihood of experiencing such doses very small, given that the representative accident producing the dose could even occur (which in itself is a very implausible event).

The principal RADTRAN conservatisms that make it unlikely that these large doses would ever be realized are as follow:

- RADTRAN uses a ground level plume formulation, i.e., the highest concentration point of the plume containing the release material moves along the ground from the release point to the farthest point of the calculation. However, in 17 of the 20 representative accidents that produce high population doses, the source term is the result (in part) of a significant fire event. These fires are hot, fully engulfing, and of duration exceeding 1 hour. In reality, a fire of sufficient duration and temperature to cause a release would cause the released plume to be lofted to an altitude in which the centroid is hundreds of meters off the ground surface. In such situations, zero or extremely low doses will be realized inside of distance that are 10 or more times the lofted height. Beyond that distance the calculated maximum doses will approach those predicted by RADTRAN , but certainly are below 5 rem. The remaining three doses also result from release plumes that are likely to be lofted, though not by the presence of a major fire, though it is likely that there will be fires present near accidents with these collision/impact magnitudes. Lofting for these plumes is a result of the fact that the major component of the gas pressurizing the cask is helium which has a density one seventh that of air. Thus, the plumes from these accidents (even in the absence of a fire) will also be lofted and the resultant dose will be lower than predicted.

- RADTRAN assumes that no measures will be taken by emergency response personnel to limit the progression of the accident. In urban and suburban and most rural areas where people could be exposed, emergency response actions will limit the chain of events that produce many of the source terms and thus act to preclude such releases. In remote areas where there are few people, it is unlikely that there will be any one within the relatively small area of high dose to receive it. Even more unlikely is that individuals would remain close to the scene of an accident and stay outside directly in the passage of a radioactive plume (that looks like a fire cloud/smoke) for the entire passage of the plume.

Thus, in spite of the predicted high doses realized for the high severity accident cases, it is deemed unlikely that the predicted doses would ever be realized in an accident situation. More importantly, it is assumed in this analysis that such accidents can occur, but, in fact, the combination of circumstances needed to release material from a modern spent fuel cask are so improbable as to be impossible.

8.15 Effect of NUREG-0170 Source Term and Exposure Pathway Models on Dose Risk

The treatments of spent fuel accident source terms and exposure pathways used in RADTRAN 5 differ markedly from those used in RADTRAN 1. This section describes these treatments and the effects they have on predictions of population dose risks in three steps. First, the inventories, accident source term equations, and exposure pathways models used in NUREG-0170 are contrasted with those used in this study. Second, results of RADTRAN 4 and RADTRAN 5 calculations are compared to RADTRAN 1 results in order to show that these codes can be made to mimic RADTRAN 1 results. Finally, a series of RADTRAN 5 calculations are performed that depict the effect of the NUREG-0170 source term and exposure pathway treatments on predictions of population dose risks.

8.15.1 Source Term and Exposure Pathway Models in RADTRAN 1 and RADTRAN 5

Both RADTRAN 1 and RADTRAN 5 calculate spent fuel accident source terms (ST_i) as the product of an inventory ($I_{inventory,i}$) of radionuclide I and the fraction ($f_{release,i}$) of that inventory that could be released to the atmnosphere should the spent fuel cask fail during a severe accident. Thus, $ST_i = I_{inventory,i}\, f_{release,i}$.

In Section 1.2, it was stated that, as it was used in NUREG-0170, $I_{inventory,i}$ is not a cask inventory. Instead, it is the number of curies of radionuclide i estimated to be released from the spent fuel cask to the atmosphere should the cask fail during a severe accident. Thus, for the RADTRAN 1 calculations performed for NUREG-0170, $I_{inventory} = ST_{severe\ accident,i}$, where values for $ST_{severe\ accident,i}$ were developed largely on the basis of conservative engineering judgment and $ST_{severe\ accident,i}$ is the source term for a severe spent fuel accident. Accordingly, as used for NUREG-0170, $f_{release,i}$ is the fraction of the severe accident source term that is released during accidents of lessor severity.

For this study, the number of curies of radionuclide i that is released from a Type B spent fuel cask should the cask and some of the rods in the cask both fail during an accident is calculated as the product of five numbers: the number of assemblies in the cask ($N_{assemblies}$), the inventory of radionuclide i in a single fuel assembly (I_i), the fraction of the number of rods in an assembly that fail (f_{rods}), the fraction of the inventory of radionuclide i in a single rod that escapes to the cask interior upon rod failure ($f_{rod\text{-}to\text{-}cask,i}$), and the fraction of the amount of radionuclide i that reaches the cask interior that escapes from the cask interior through the cask leak to the environment ($f_{cask\text{-}to\text{-}environment,i}$). Thus, for this study, the source term for radionuclide i (ST_i) is calculated as

$$ST_i = N_{assemblies} I_i f_{rods} f_{rod\text{-}to\text{-}cask,i} f_{cask\text{-}to\text{-}environment,i}$$

where $I_{inventory,i} = N_{assemblies} I_i$ and $f_{release,i} = f_{rods} f_{rod\text{-}to\text{-}cask,i} f_{cask\text{-}to\text{-}environment,i}$.

Table 7.9 shows that the single assembly BWR and PWR inventories used in this study contain 19 and 20 radionuclides, respectively. In marked contrast to Table 7.9, Table 1.4 shows that the truck and rail cask accident “inventories” used with RADTRAN 1 for the NUREG-0170 spent fuel calculations contain only three radionuclides, Kr-85, I-131, and Cs-137. Here “inventories” is in quotes to emphasize the fact that the NUREG-0170 meaning for this term is different from the common meaning. That is, in NUREG-0170 [8-1], "inventory" means the amount of each radionuclide released to the environment upon package failure and not the amount of each radionuclide that is contained (carried) in the package, here the Type B spent fuel cask. Table 7.9 shows that the BWR and PWR inventories developed for this study do not contain I-131. They do not contain I-131 because the RADSEL code calculation described in Section 7.2.3.3 showed that iodine radionuclides in three-year cooled, high-burnup spent fuel do not contribute significantly to radiation health hazards at the level of one-tenth of one percent.

Table 7.31 shows that the source term analysis performed for this study developed 19 source terms for a steel-lead-steel Type B spent fuel truck cask, one of which, Case 19, represents the fraction of all truck accidents that do not lead to a release of radioactivity from the cask because either the cask containment is not compromised or because none of the rods in the cask fail. The table also shows that for a steel-lead-steel Type B spent fuel rail cask, 21 source terms were developed, one of which represents accidents that do not lead to any release of radioactivity. As described in Section 1.2, the source term scheme used in NUREG-0170 [8-1] had eight categories and two release models, Models I and II. Categories I and II represented accidents that respectively do not result in releases from Type A and Type B packages. Categories III through VIII represented accidents that are severe enough to cause radionuclides to be released from a Type B package. Both release models assumed that all materials released from the cask were respirable, that is they were either gases, vapors, or respirable aerosols. Thus, all solid materials released from the cask were assumed to be aerosols with sizes (aerodynamic mass median diameters) $\leq 10\ \mu$. Model I assumed that 100 percent of the NUREG-0170 truck and rail accident "inventories" of Kr-85, I-131, and Cs-137 was released by any accident that fell into Categories III through VIII. Model II tempered this conservative assumption by decreasing the fraction of the NUREG-0170 accident "inventories" released for Categories III and IV accidents from 100 percent to 1 and 10 percent respectively.

RADTRAN 5 models radiation exposures caused by transportation accidents that are delivered via four pathways: direct exposure to the passing radioactive airborne plume (cloudshine), exposures caused by inhalation of radioactive materials in the passing airborne plume (direct inhalation), exposures to radioactivity deposited onto the ground from the passing airborne plume (groundshine), and exposures caused by inhalation of radioactive materials that are resuspended from contaminated ground into the air (resuspension inhalation). In marked contrast to this, RADTRAN 1 only modeled inhalation exposures (both direct inhalation and resuspension inhalation).

Two sets of calculations were performed to examine the impact on estimates of accident consequences calculated with RADTRAN 1 and RADTRAN 5 of these differing treatments of accident source terms and exposure pathways. The first set of calculations compared the mean accident population doses and the mean number of latent cancer fatalities that are obtained when the NUREG-0170 spent fuel transport accident calculation is run using RADTRAN 1, RADTRAN 4, and RADTRAN 5. The second set of calculations examined the impact of various combinations of these treatments on RADTRAN 5 steel-lead-steel truck cask accident CCDFs.

8.15.2 Comparison of Results Calculated with RADTRAN Versions 1, 4, and 5

When this study was initiated, RADTRAN 1, the first version of the RADTRAN code that was developed to support the performance of NUREG-0170 [8-1], existed only as a listing on microfiche appended to the Sandia National Laboratories report that describes RADTRAN 1 [8-8]. Thus, for this study, in order to compare RADTRAN 1 results to results obtained with later versions of the RADTRAN code, RADTRAN 1 had again to be made operational. Reference [8-9] describes the resurrection and verification of RADTRAN 1.

Ideally, RADTRAN 1 results would be compared directly to results obtained using RADTRAN 5, the version of the RADTRAN code used to support this study. This was not done for the following reasons. RADTRAN 1 is able to examine only one radionuclide at a time. Accordingly, three RADTRAN 1 calculations must be performed to develop results for the three radionuclides (Kr-85, I-131, and Cs-137) in the NUREG-0170 spent fuel accident "inventory." RADTRAN 4 and RADTRAN 5 can examine many radionuclides during a single calculation. However, while RADTRAN 4 can output the accident population dose attributable to each radionuclide examined, RADTRAN 5 outputs only the total population dose and not the doses attributable to the individual radionuclides in its package inventory. Further, differences in code input mean that essentially identical input can be developed for RADTRAN 1 and RADTRAN 4 or for RADTRAN 4 and RADTRAN 5, but not for RADTRAN 1 and RADTRAN 5. Because RADTRAN 4 and RADTRAN 5 yield essentially identical results for the NUREG-0170 spent fuel calculation (i.e., total truck and train accident population doses respectively of 2.12E+02 versus 2.13E+02 person-rem), RADTRAN 4 results are an excellent surrogate for RADTRAN 5 results. Therefore, because identical input could be developed for RADTRAN 1 and RADTRAN 4 and because RADTRAN 4 generates population dose results for each radionuclide examined, the calculations that compared accident doses compared RADTRAN 1 results to those obtained with RADTRAN 4.

Replication of RADTRAN 1 input data in the formats required by RADTRAN 4 and RADTRAN 5 was not simple for all input parameters. For example, in RADTRAN 4, the fraction of land occupied by buildings is 0.52, fixed values are used for the fractions of the population that are outdoors and in buildings, and doses for people in buildings are calculated by multiplying the dose for people outdoors by a building dose factor (BDF) which accounts for the lower doses that are received by people in buildings because of particle filtering during air infiltration into buildings. Because RADTRAN 1 does not model the particle filtration during air infiltration into buildings, in order to force RADTRAN 4 to mimic RADTRAN 1, the value of BDF used in the RADTRAN 4 calculations was chosen so $0.52 \times \text{BDF} = 1.0$, which made RADTRAN 4 doses for people in buildings the same as the doses received by people outside of the buildings. For RADTRAN 5, because the fraction of land occupied by buildings and the BDF are both input parameters, RADTRAN 5 could be made to mimic RADTRAN 1 by setting both of these parameters equal to 1.0. RADTRAN 4 and RADTRAN 5 but not RADTRAN 1 calculate pedestrian doses in urban areas. Therefore, for the RADTRAN 4 and RADTRAN 5 calculations, this dose was forced to zero by setting the value of RPD, the ratio of pedestrian density to region population density, to zero. Finally, the value of the inhalation dose conversion factor currently used for RADTRAN 4 and RADTRAN 5 calculations, which is somewhat larger than the value used in RADTRAN 1, was reset to the RADTRAN 1 value.

Table 8.15 presents the mean accident population dose risks predicted by RADTRAN 1 and RADTRAN 4 for the NUREG-0170 truck and rail calculations when each code was run using the same truck or rail route and the same truck or rail accident source terms (i.e., the NUREG-0170 truck or rail route, the NUREG-0170 truck or rail accident "inventory" specified in Table 1.4, and the NUREG-0170 Model II severity and release fractions specified in Table 1.3). Two sets of RADTRAN 4 results are presented. The first set models only inhalation exposures (both the dose from inhalation of radioactive materials directly from the passing plume and the dose caused by inhalation of radioactive materials that are resuspended from the ground), while the second set models not only direct and resuspension inhalation exposures but also exposures from cloudshine and groundshine. Thus, the first set of results is directly comparable to the results generated by RADTRAN 1 while the second set reflects the more complete treatment of exposure pathways as currently modeled in both RADTRAN 4 and RADTRAN 5.

Table 8.15 Mean Accident Population Dose Risks Calculated by RADTRAN 1 and RADTRAN 4 (person-rem)

Radionuclide	Code (Exposure Pathways)		
	RADTRAN 1 (only inhalation and resuspension)	RADTRAN 4 (only inhalation and resuspension)	RADTRAN 4 (all pathways)
NUREG-0170 Truck Route and Truck Accident Model II Source Terms			
Kr-85	1.05E-04	1.83E-04	4.20E-01
I-131	2.68E-03	2.66E-03	2.69E-03
Cs-137	1.32E+00	4.34E+00	1.79E+02
NUREG-0170 Rail Route and Rail Accident Model II Source Terms			
Kr-85	2.32E-05	3.73E-05	8.52E-02
I-131	5.76E-04	5.29E-04	5.33E-04
Cs-137	2.89E-01	8.78E-01	3.20E+01

Table 8.15 shows that

- that the doses caused by the quantities of Kr-85 and I-131 in the NUREG-0170 truck and train accident "inventories" contribute negligibly to the total accident population doses (sum of the doses caused by each radionuclide), which are essentially equal to the dose caused by Cs-137;

- that the RADTRAN 4 total inhalation truck and rail accident population doses are respectively 3.3 and 3.0 times larger than the corresponding RADTRAN 1 doses; and

- that the truck and rail accident population doses calculated by RADTRAN 4, when all exposure pathways are modeled, are respectively about 41 and 36 times larger than the doses calculated when only the direct inhalation and resuspension inhalation pathways are modeled.

Differences between the RADTRAN 1 and RADTRAN 4 inhalation dose models explain the second result. Specifically, in the RADTRAN 1 and RADTRAN 4 equations for D_{inh}, the total inhalation dose (sum of the direct and resuspension inhalation pathway doses) are formed into a ratio and common parameters that have the same value are cancelled, the following expression results

$$\frac{D_{inh}(\mathrm{RADTRAN\,4})}{D_{inh}(\mathrm{RADTRAN\,1})} = \frac{\mathrm{IF\ x\ BR}}{2.223\mathrm{E}-2} \times \frac{\mathrm{RESUSP(RADTRAN\,4)}}{\mathrm{RESUSP(RADTRAN\,1)}} = 3.3$$

This expression equals 3.3 because in RADTRAN 4, the time-integrated atmospheric dilution factor, IF = 66.2 Ci s/m^2 for Cs-137, the breathing rate, BR = 3.3E-4 m^3/s, and the resuspension factor, RESUSP = 5.41, while in RADTRAN 1 the constant 2.223E-2 represents the product of a time integrated atmospheric dilution factor and a breathing rate, and RESUSP = 1.62. Thus, the fact that RADTRAN 4 truck and rail accident population doses are respectively 3.3 and 3.0 times larger that the same doses calculated with RADTRAN 1 is almost entirely caused by the differences in the parameter values used in the nearly identical RADTRAN 1 and RADTRAN 4 inhalation dose models.

RADTRAN 1, RADTRAN 4, and RADTRAN 5 all estimate the radiation induced latent cancer fatalities (LCFs) that may occur among a population exposed to radiation due to the transport of a radioactive material, for example spent fuel. Because RADTRAN 1 and RADTRAN 4 use different models to calculate LCF values, comparison of the LCF predictions of these two versions of RADTRAN is not straightforward. However, because both RADTRAN 1 and RADTRAN 5 calculate LCFs from population dose using a simple multiplicative cancer fatality risk factor, the cancer fatality models in these two versions of RADTRAN can be made the same by setting the value of this factor in RADTRAN 5 to 2.220E-05 LCFs/person-rem, the hardwired value that is used in RADTRAN 1 to calculate cancer fatalities caused by inhalation dose to the lungs, or to 1.216E-4 LCFs/person-rem, the value used to calculate cancer fatalities from the dose delivered to the whole body by all exposure pathways.

Table 8.16 presents the predictions of LCF risks for the NUREG-0170 standard spent fuel shipment model for the year 1975 (i.e., 17 rail shipments of length 1,210 km and 254 truck shipments of length 2,530 km) obtained using RADTRAN 1, RADTRAN 4, and RADTRAN 5, the NUREG-0170 truck and rail accident "inventories," and the NUREG-0170 Model II Severity

Table 8.16 RADTRAN 1, RADTRAN 4, and RADTRAN 5 Estimates of the Mean Latent Cancer Fatality Risks Associated with Shipment of Spent Fuel According to the NUREG-0170 Standard Shipment Model for 1975

Code Version (pathways modeled)	Mean Latent Cancer Fatality Risk
RADTRAN 1 (only direct and resuspension inhalation)	3.57E-05
RADTRAN 4 (only direct and resuspension inhalation)	1.15E-04
RADTRAN 5 (only direct and resuspension inhalation)	1.16E-04
RADTRAN 4 (all pathways)	2.50E-02
RADTRAN 5 (all pathways)	2.54E-02

and Release Fractions. Table 8.16 shows that the RADTRAN 5 and RADTRAN 1 LCF predictions differ by a factor of 3.3 when RADTRAN 5 is made to model only the direct and resuspension inhalation pathways, while the RADTRAN 5 result when all exposure pathways are modeled is 700 times larger than the result obtained using RADTRAN 1, which models only inhalation pathways.

Because RADTRAN 4 inhalation doses exceed those predicted by RADTRAN 1 by factors of approximately 3.3, the mean latent cancer fatality prediction of RADTRAN 4 also exceeds that of RADTRAN 1 by about 3.3. Because the dosimetric models in RADTRAN 4 and 5 are essentially identical, and their cancer risk models are equivalent, RADTRAN 4 and RADTRAN 5 yield essentially identical predictions of latent cancer fatalities when these fatalities are based only on inhalation dose and also when they are based on dose delivered by all exposure pathways.

The preceding results demonstrate that RADTRAN 4 and RADTRAN 5 yield nearly identical latent cancer fatality predictions when both run the same problem. Therefore, because RADTRAN 4 inhalation doses exceed those predicted by RADTRAN 1 by a factor that is almost entirely explicable in terms of differences in a few inhalation dose parameter values, the fact that RADTRAN 4 and RADTRAN 5 yield identical results for the same problem means that RADTRAN 5 is a reasonable surrogate for RADTRAN 1. Accordingly, RADTRAN 5 was used to examine the impact that the various components of the NUREG-0170 treatments of source terms and exposure pathways have on population dose CCDFs.

8.15.3 Effect of Treatments on RADTRAN 5 Accident Population Dose CCDFs

Because the accident source terms developed for NUREG-0170 [8-1] are very different from those developed for this study and because RADTRAN 1 models only inhalation exposures while RADTRAN 5 models cloudshine and groundshine exposures in addition to inhalation exposures, five RADTRAN 5 truck transport calculations were performed to illustrate the effect of these different treatments on accident population dose risk. Except for source terms, the input data used in these five calculations (the LHS sample and the values for all other parameters except source term parameters) was identical. Thus, each calculation used the same set of 200 representative routes and route characteristics, and each used the same set of values for all other input parameters except severity fractions and release fractions. Table 8.17 lists for each calculation the source term used, the exposure pathways modeled, and the resulting Mean Accident Population Dose Risk.

Figure 8.25 presents the five Accident Population Dose Risk CCDFs developed by these calculations. Figure 8.25 shows that the five Accident Population Dose Risk CCDFs are ordered as follows:

Calc. 19 CCDF > Calc. 20 CCDF > Calc. 21 CCDF > Calc. 22 CCDF > Calc. 1 CCDF

where > means "lies above." Calculation 1 in Tables 8.1 and 8.17 is the RADTRAN 5 calculation that examined the risks associated with the transport of a single PWR assembly in the generic steel-lead-steel truck cask and used as input (a) the LHS sample of size 200 that

Table 8.17 Mean Accident Population Dose Risks (person-rem) for Five RADTRAN 5 Calculations that Used Different Source Terms and Exposure Pathways

Calculation Number from Table 8.1	Inventory		Severity and Release Fractions			Exposure Pathways		Mean Accident Population Dose Risk
	PWR[a]	0170[b]	0170[c]		SLS-T[d]	All	Inhalation Only	
			Model I	Model II				
19	X		X			X		1.2E+4
20	X			X		X		7.0E+2
21		X		X		X		2.2E-2
22		X		X			X	7.7E-4
1	X				X	X		8.0E-7

a. See Table 7.9.
b. See Table 1.4.
c. See Table 1.3 in this report and Table 5-8 in Reference [8-1].
d. See Table 7.31.

contained the set of 200 representative truck routes and (b) the set of 19 new steel-lead-steel truck cask source terms developed by this study. Calculation 22 in these tables is the RADTRAN 5 calculation that best replicates, when 200 representative routes are examined, the NUREG-0170 accident population dose risk results for the shipment of a single spent fuel truck cask. Although the CCDFs for these two calculations cross at a population dose of about 2E+3 person-rem, Table 8.17 shows that the mean accident population dose risk for Calculation 22, the calculation that used the NUREG-0170 truck accident source term and modeled only inhalation exposures, is 1000 times larger than the mean accident population dose risk predicted by Calculation 1, the steel-lead-steel truck transport calculation that used the 19 truck accident source terms developed for this study and modeled all exposure pathways. Comparison of the mean accident population dose risk results for Calculations 22 and 21, 21 and 20, and 20 and 19 then shows, respectively, that modeling cloudshine and groundshine increases mean accident population dose risks by about a factor of 30; using the PWR cask inventory instead of the NUREG-0170 truck accident "inventory," which represents the radioactivity released to the environment by the most severe accidents examined by NUREG-0170 [8-1], greatly increases mean accident population dose risks by a factor of about 30,000; and finally, replacing the NUREG-0170 Model II severity and release fractions by the Model I severity and release fractions pushes the knee of the CCDF up a bit and further increases mean accident population doses by a factor of about 20. Mean accident population dose risks increase by a factor of 30,000 when the NUREG-0170 accident "inventory" is replaced by the PWR truck cask inventory, because the NUREG-0170 Models I and II treat all solid materials released as 100 percent aerosolized and 100 percent respirable. Thus, use of a real cask inventory with these assumptions means that all of the actinides in spent fuel contribute to inhalation doses, which greatly increases direct inhalation doses and very greatly increases long-term resuspension inhalation doses.

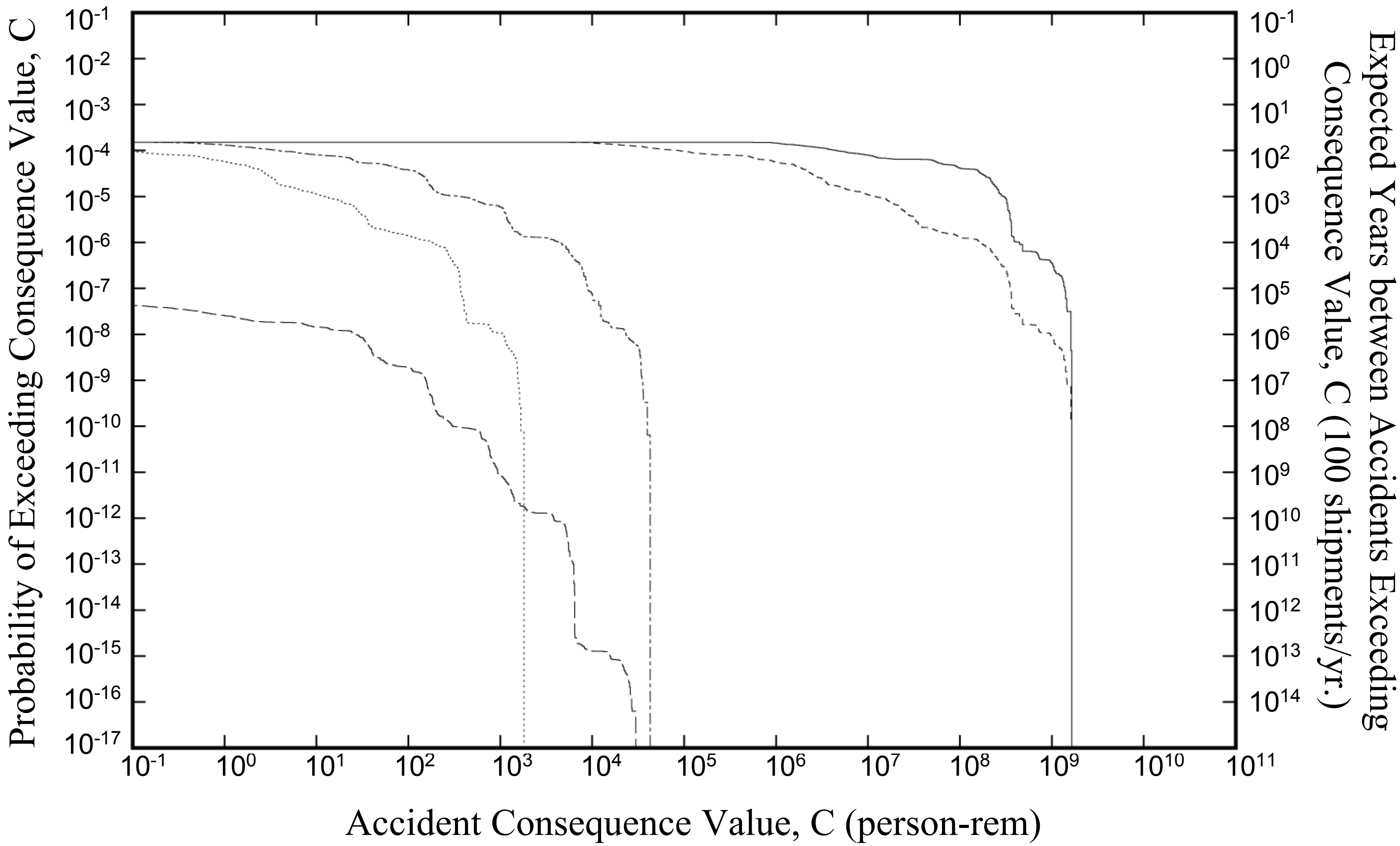

Figure 8.25 Mean truck accident population dose risk CCDFs for calculations that examined the impact on dose risks of NUREG-0170 source terms and exposure pathway models. Each RADTRAN 5 calculation assumed transport in a steel-lead-steel truck cask over each of the 200 representative truck routes and each calculation generated results for all of the 19 representative truck accident source terms.

——— **PWR inventory, NUREG-0170 Model I release fractions, all exposure pathways**

------------ **PWR inventory, NUREG-0170 Model II release fractions, all exposure pathways**

-·-·-·- **NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, all exposure pathways**

······· **NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, only inhalation pathways**

– – – PWR inventory, 19 truck accident source terms, all exposure pathways

8.16 Population Dose Risk CCDFs from NUREG-0170, the Modal Study, and this Study

Because the spent fuel risk assessment methodology developed by the Modal Study [8-2] was the basis for all of the analyses conducted by this study, it is of interest to compare accident population dose risk CCDFs and mean accident population doses calculated by RADTRAN 5 using NUREG-0170 Model I and Model II source terms, Modal Study source terms, and the source terms developed by this study. Each of these calculations examined transport of PWR spent fuel in a steel-lead-steel spent fuel cask and used the LHS sample of size 200 that contained the representative set of 200 truck or rail routes. Except for inhalation dose and source term parameters, each calculation used the same set of parameter values for all parameters that had fixed values. Thus, the calculations differed only in the sets of source terms used and in their treatments of exposure pathways (the NUREG-0170 calculations modeled only inhalation dose while the Modal Study calculation and the calculation that used the source terms developed for this study modeled all exposure pathways). Accordingly, these calculations compare the NUREG-0170 result to the Modal Study result and to the result developed by this study.

The NUREG-0170 Model I and Model II source terms were presented in Table 1.5. Table 8.18 presents the Modal Study truck and rail accident source terms developed for generic steel-lead-steel casks. The source terms developed by this study for generic steel-lead-steel casks were presented in Table 7.31.

Figures 8.26 and 8.27 present respectively the truck and rail accident population dose risk CCDFs generated by these calculations. Each figure presents four CCDFs: the NUREG-0170 Model I CCDF, the NUREG-0170 Model II CCDF, the Modal Study CCDF, and the CCDF developed by this study. In each figure, the highest lying CCDF is the NUREG-0170 Model I CCDF, the next highest is the NUREG-0170 Model II CCDF, the next is the Modal Study CCDF, and the lowest lying CCDF is the CCDF developed by this study. The impact of the differences in the source term models used to generate these CCDFs can best be understood by comparing the probability and consequence axis intercepts of these CCDFs and the mean population dose risk associated with each CCDF (the area under each CCDF). The values of the CCDF intercepts and the areas under each CCDF (the mean accident population dose risk) are presented in Table 8.19.

8.16.1 CCDF Probability Axis Intercepts

The probability axis intercepts of the CCDFs in Table 8.19 can each be viewed as the product of an average accident probability per shipment (averaged over the 200 representative truck or rail routes examined) and one minus the chance that the shipment occurs without an accident severe enough to cause the spent fuel cask to fail and release radioactivity to the atmosphere. Tables 1.5, 8.18, and 7.31 show that the chance that an accident will not be severe enough to fail a spent fuel cask was estimated by NUREG-0170 [8-1], the Modal Study [8-2], and this study to be 0.91, 0.994316, and 0.99993, respectively, for truck accidents, and 0.80, 0.993962, and 0.99996, respectively, for rail accidents. But all of the truck calculations used the same set of truck route data and all of the train calculations used the same set of rail route data. So the average accident probability per truck shipment was the same for all truck calculations and the average accident probability per rail shipment was the same for all train shipments. Therefore, ratios of

Table 8.18 Modal Study Truck and Rail Accident Source Terms

Bin	F(rod) (Fig. 8-3)[a]	Release Fractions (Table 8.3[a])					Source Term Fractions = F(rod) × Release Fractions					Severity Fraction	
		Kr	Cs	Ru	Particulates	CRUD	Kr	Cs	Ru	Particulates	CRUD	Truck (Fig. 7-10)[a]	Rail (Fig. 7-11)[a]
1,1	0.03	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.994316	0.993962
2,1	0.03	2.0E-01	2.0E-04	2.0E-05	2.0E-06	2.0E-06	6.0E-03	6.0E-07	6.0E-08	6.0E-08	6.0E-07	3.8192E-03	2.7204E-03
3,1	0.03	2.0E-01	2.0E-04	2.0E-05	2.0E-06	2.0E-06	6.0E-03	6.0E-07	6.0E-08	6.0E-08	6.0E-07	1.7984E-03	5.5450E-04
1,2	0.1	1.3E-01	1.0E-06	6.7E-06	2.0E-06	2.0E-06	1.3E-02	1.0E-07	6.7E-07	2.0E-07	2.0E-07	1.6870E-05	1.2275E-03
2,2	0.1	1.3E-01	1.0E-06	6.7E-06	2.0E-06	2.0E-06	1.3E-02	1.0E-07	6.7E-07	2.0E-07	2.0E-07	2.3300E-07	5.0110E-07
3,2	0.1	1.3E-01	1.0E-06	6.7E-06	2.0E-06	2.0E-06	1.3E-02	1.0E-07	6.7E-07	2.0E-07	2.0E-07	1.5740E-07	1.0210E-07
1,3	1.0	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	2.3620E-05	7.9511E-04
2,3	1.0	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	3.0080E-07	3.2550E-07
3,3	1.0	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	3.3E-01	2.0E-04	2.7E-05	2.0E-06	2.0E-06	2.0340E-07	6.6340E-08
1,4	1.0	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	1.5250E-05	6.1400E-04
2,4	1.0	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	1.5920E-07	2.5310E-07
3,4	1.0	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	3.9E-01	2.0E-04	4.8E-05	2.0E-06	2.0E-06	1.0760E-07	5.1620E-08
4,1	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	1.5320E-07	1.7860E-09
4,2	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	3.9260E-14	3.2900E-13
4,3	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	1.4950E-14	2.1370E-13
4,4	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	7.6810E-16	1.6440E-13
1,5	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	9.5700E-06	1.2490E-04
2,5	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	7.2010E-08	1.0750E-08
3,5	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	4.8370E-08	5.2960E-08
4,5	1.0	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	6.3E-01	2.0E-03	4.8E-04	2.0E-05	2.0E-05	1.0000E-16	3.4500E-14

a. Cited figures and tables are in the Modal Study, Reference [8-2].

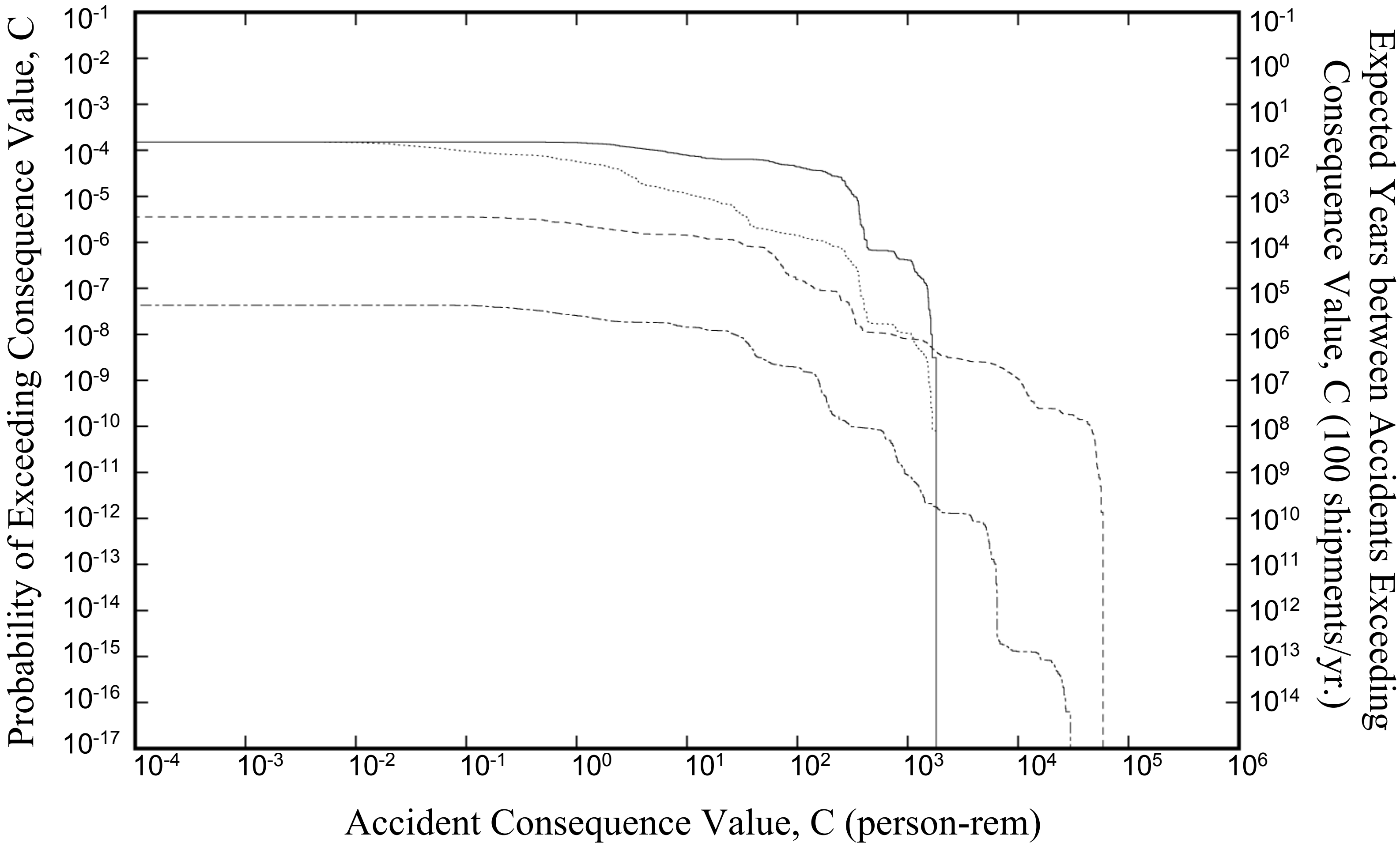

Figure 8.26 Mean truck accident population dose risk CCDFs for calculations that compared the source terms developed by NUREG-0170, the Modal Study, and this study. Each RADTRAN 5 calculation assumed transport in a steel-lead-steel truck cask over each of the 200 representative truck routes and each calculation generated results for all of the 19 representative truck accident source terms.

——— **NUREG-0170 accident release inventory, NUREG-0170 Model I release fractions, only inhalation pathways**

······ **NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, only inhalation pathways**

------------ **PWR inventory, 20 Modal Study source terms, all exposure pathways**

-·-·-·- **PWR inventory, 19 truck accident source terms developed for this study, all exposure pathways**

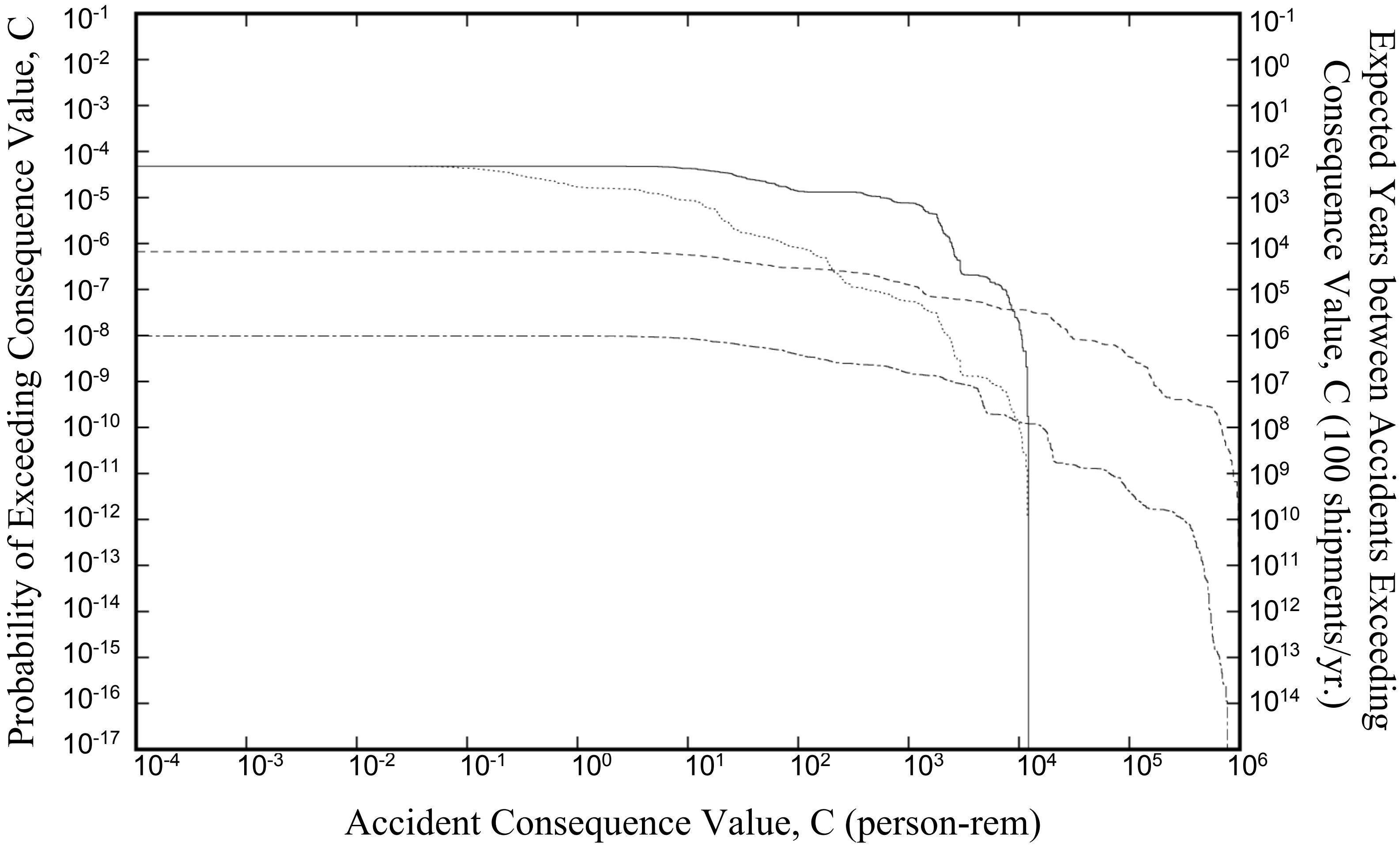

Figure 8.27 Mean rail accident population dose risk CCDFs for calculations that compared the source terms developed by NUREG-0170, the Modal Study, and this study. Each RADTRAN 5 calculation assumed transport in a steel-lead-steel rail cask over each of the 200 representative rail routes and each calculation generated results for all of the 21 representative rail accident source terms.

——— NUREG-0170 accident release inventory, NUREG-0170 Model I release fractions, only inhalation pathways

······· NUREG-0170 accident release inventory, NUREG-0170 Model II release fractions, only inhalation pathways

------------ PWR inventory, 20 Modal Study source terms, all exposure pathways

-·-·-·-·- PWR inventory, 19 truck accident source terms developed for this study, all exposure pathways

Table 8.19 Comparison of NUREG-0170 Model I and Model II and Modal Study Probability and Consequence Axis CCDF Intercepts to Those Developed by this Study

	Truck Accident CCDFs	Train Accident CCDFs
Probability Axis Intercepts		
NUREG-0170 Model I	1.5E-4	4.8E-4
NUREG-0170 Model II	1.5E-4	4.8E-4
Modal Study	3.6E-6	6.8E-7
This Study	4.4E-8	9.4E-9
Consequence Axis Intercepts		
NUREG-0170 Model I	1.8E+3	1.2E+4
NUREG-0170 Model II	1.8E+3	1.2E+4
Modal Study	6.0E+4	1.0E+6
This Study	3.0E+4	7.7E+5
Mean Accident Population Dose Risk		
NUREG-0170 Model I	1.3E-2	1.9E-2
NUREG-0170 Model II	7.7E-4	4.9E-4
Modal Study	1.3E-4	1.9E-3
This Study	8.0E-7	9.4E-6

probability intercepts ought to qualitatively equal ratios of the differences from one of the chance that the shipment takes place without a severe accident occurring. As the ratios in Table 8.20 show, within a factor of about two, this prediction holds true.

Table 8.20 Ratios of Probability Axis Intercepts

	Truck		Rail	
	Ratio Probability Intercepts	Ratio Values of 1- $f_{\text{not severe accident}}$	Ratio Probability Intercepts	Ratio Values of 1- $f_{\text{not severe accident}}$
NUREG-0170/Modal Study	42	16	71	33
Modal Study/This Study	82	81	70	151

This simple analysis shows that the values of the probability axis intercepts on the truck or train accident population dose risk CCDFs are primarily determined by the substantially different estimates developed by each study of the chance that an accident will not be severe enough to cause radionuclides to be released from a spent fuel cask.

The estimates of the fraction of all accidents that lead to radionuclide release from a spent fuel cask differ greatly because whenever cask failure was examined in greater detail, first by the Modal Study [8-2] and then by this study, the chance of encountering impact or thermal loads able to fail a spent fuel cask was found to decrease substantially. For example, the eight-category accident scheme used in the NUREG-0170 analyses derives its severity fraction values from analyses performed by Clarke, et al. [8-10], who estimated the fraction of all truck and train accidents that were "minor, moderate, severe, extra severe, or extreme." For NUREG-0170, the probabilities of the accidents assigned to each of these five severity categories were reapportioned into two categories that did not lead to cask failure and six that did (the NUREG-0170 Categories I through VIII). When this was done, some of the accidents that fell into the "minor" accident category of Clarke, et al. were judged to be able to cause cask failure, and the "extra severe" and "extreme" categories were split into three categories that became NUREG-0170 Categories VI, VII, and VIII. Inspection of the boundaries between the "minor" and "moderate" truck and rail accident categories of Clarke, et al. shows that some "minor" accidents might involve fires with durations less than 10 minutes, punctures with impact speeds of only a few miles per hour, and crush loadings less than 20,000 pounds. Because some "minor" accidents were apportioned into NUREG-0170 accident Category III, these conditions for the boundary between "minor" and "moderate" accidents show that NUREG-0170 [8-1] made very conservative assumptions about the accident conditions that might produce cask failure. Because of these conservative assumptions, NUREG-0170 found that 9 percent of all truck accidents and 20 percent of all rail accidents were severe enough to fail a spent fuel cask.

The finite element and thermal analyses of cask response to impact and thermal loads performed by the Modal Study [8-2] allowed the NUREG-0170 estimates of the chance of failure of spent fuel truck and rail casks to be lowered respectively by factors of 16 and 33 to 0.57 and 0.60 percent. Moreover, when the Modal Study methodology was extended by this study to allow examination of the response of the cask closure to mechanical and thermal loads, the chance that a severe accident would fail a truck or a rail cask was estimated to be even smaller, specifically, 0.007 percent for truck casks and 0.004 percent for rail casks.

8.16.2 CCDF Consequence Axis Intercepts

Consequence axis intercept values give the largest accident population dose calculated during any of the many trials (cases) examined by a single RADTRAN run. In the absence of decontamination or interdiction of contaminated property, the largest population dose calculated would be expected to be approximately proportional to the size of the radioactive release. However, because the RADTRAN code interdicts ground that (a) is contaminated above an input contamination criterion and (b) cannot be decontaminated to levels less than or equal to the criterion, the maximum population dose calculated (i.e., the consequence axis intercept) may not be caused by the largest set of release fractions examined during the calculation. Despite the complications introduced by decontamination and interdiction, the relative values of the consequence axis intercepts presented in Table 8.17 are instructive.

As Table 8.17 shows, the maximum values of the accident population doses listed in Table 8.17 and depicted in Figures 8.25 and 8.26 are ordered as follows: Modal Study value > value from this study > NUREG-0170 value. As the table shows, the maximum accident population doses calculated by the Modal Study [8-2] and by this study for truck accidents and also for rail accidents differ only slightly (by a factor of two or less). This was to be expected because both accident population dose calculations used the same cask inventory, both assumed failure of all of the rods in the cask for the most severe accidents, both used rod-to-cask release fractions based on the experimental results of Lorenz, and both assumed no deposition onto cask surfaces of materials released to the cask interior from failed spent fuel rods (the Modal Study assumed

$f_{\text{cask-to-environment}}$ = 1.0 for all accidents; this study assumed $f_{\text{cask-to-environment}}$ = 1.0 for the most severe accidents, i.e., for all Category 6 accidents, which by definition involve a double cask failure).

Although NUREG-0170 source terms contain only Kr-85, I-131, and Cs-137, NUREG-0170 accident population doses are essentially caused exclusively by the Cs-137 in the source term. Therefore, one would expect the ratio of the maximum NUREG-0170 rail accident population dose and the maximum NUREG-0170 truck accident population dose (the NUREG-0170 consequence axis intercepts listed in Table 8.17) to about equal the ratio of Cs-137 in the NUREG-0170 source terms. The NUREG-0170 Cs-ratio (rail/truck) is 6.4 = 1280 Ci/200 Ci and the NUREG-0170 population dose ratio is 15. So again, the predicted and observed results agree to about a factor of two. However, because interdiction would be expected to perturb the dose caused by the larger release more than that caused by the smaller release, the ratio of the train accident maximum population dose to the truck accident population dose might have been expected to be less than rather than, as is observed, greater than 6.4.

Because the NUREG-0170 accident population doses are entirely caused by Cs-137 and because the maximum amount of Cs-137 that can be released by these source terms is fixed at 200 Ci for truck accidents and 1280 Ci for rail accidents, maximum NUREG-0170 accident population doses are in effect capped. In contrast to this, because the Modal Study source terms and the source terms developed for this study are both calculated as the product of a PWR cask inventory that contains 19 radionuclides, a rod failure fraction, and a set of rod-to-cask and cask-to-environment release fractions, the source term constructs developed by the Modal Study [8-2] and by this study allow larger releases (larger source terms) to occur than are allowed to occur by the NUREG-0170 source term construct. Accordingly, the fact that both the Modal Study calculation and the calculation of this study both predict maximum accident population doses that are larger than those predicted by the NUREG-0170 calculation was to be expected.

Comparison of the expected (mean) accident population dose risks and dose risk CCDFs obtained using NUREG-0170 Model I and Model II source terms shows that, although both calculations yield CCDFs that have identical probability and consequence axis intercepts, the Model I expected accident population dose risk is about 17 times greater for truck accidents and about 39 times greater for rail accidents than the Model II dose risk. This clearly shows that dose risk is determined by the area under the CCDF in the region where the CCDF bends over and then plunges toward the consequence axis.

Each of these calculations examined transport of PWR spent fuel assemblies in steel-lead-steel spent fuel casks and each used the same PWR assembly inventory. For truck and rail transport, the cask was assumed to carry, respectively, 1 and 24 assemblies. Therefore, because the release fractions for the largest truck and train accident source terms of this study and the Modal Study are very similar, the ratio of the maximum accident population doses predicted using these source terms (the consequence axis intercepts of the CCDFs generated by these calculations) should be approximately equal 24, the ratio of the number of assemblies carried by a rail cask to the number carried by a truck cask. In fact, as Table 8.17 shows, the ratio of these maximum doses for the Modal Study is 17 = 1E6/6E4, and the ratio for this study is 26 = 7.7E5/3.0E4.

Lastly, Table 8.17 shows that the expected accident population dose risks stand in the following order and have the following relative magnitudes when normalized to the NUREG-0170 Model I result:

Truck Accidents: NUREG-0170 Model I (1.0) > NUREG-0170 Model II (0.06) > Modal Study (0.01) > This Study (0.00006)

Rail Accidents: NUREG-0170 Model I (1.0) > Modal Study (0.1) > NUREG-0170 Model II (0.03) > This Study (0.0005)

Thus, the detailed analysis of the mechanical and thermal response of the cask shell performed by the Modal Study [8-2] shows that spent fuel cask failure is significantly less probable and spent fuel source terms substantially smaller than was estimated by NUREG-0170. In addition, the analysis of closure behavior performed by this study by extending the Modal Study methodology suggests that the probability of spent fuel cask failure and the magnitudes of spent fuel accident source terms are both much smaller than the estimates developed by the Modal Study.

8.17 References

[8-1] "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," NUREG-0170, U.S. Nuclear Regulatory Commission, December 1977.

[8-2] L. E. Fischer, et al., "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, Lawrence Livermore National Laboratory, Livermore, CA, February 1987.

[8-3] G. S. Mills et al., "Application of Latin Hypercube Sampling to RADTRAN 4 Truck Accident-Risk Sensitivity Analysis," Proceedings of the 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95), IAEA, Vol. 4, p. 705, 1995.

[8-4] "Acceptance Priority Ranking and Annual Capacity Report," DOE/RW-0457, U.S. Department of Energy, Washington DC 20585, March 1995.

[8-5] N. R. Griego, J. D. Smith, and K. S. Neuhauser, "Investigation of RADTRAN Stop Model Input Parameters for Truck Stops," Conference Proceedings, Waste Management 96, Tucson, AZ, 1996.

[8-6] Personal Communications, B. Jody (Davis Transport, November 23, 1999); R. Ledford (TriState, November 24, 1999); and Blake Williams (NAC, November 30, 1999).

[8-7] Regulations for the Safe Transport of Radioactive Material, Safety Standard Series No. ST-1/Requirements, 1996, International Atomic Energy Agency (IAEA), Vienna, Austria (reproduced in Code of Federal Regulations, Volume 10, Part 71, Appendix A).

[8-8] J. M. Taylor and S. L. Daniel, "RADTRAN: A Computer Code to Analyze Transportation of Radioactive Material," SAND76-0243, Sandia National Laboratories, Albuquerque, NM, 1977.

[8-9] P. C. Reardon, "RADTRAN 1 Release 1: Retrieval and Verification from Archive," SAND99-1149, Sandia National Laboratories, Albuquerque, NM, to be published, copy available on request.

[8-10] R. K. Clarke, et al., "Severities of Transportation Accidents, Volume III – Motor Carriers and Volume IV – Train," SLA-74-0001, Sandia National Laboratories, Albuquerque, NM, 1976.